NISTIR 5089

U.S. DEPARTMENT OF COMMERCE

Technology Administration

National Institute of Standards and Technology

Electronics and Electrical Engineering Laboratory

Electromagnetic Technology Division

Programs, Activities, and Accomplishments

The Electronics and Electrical Engineering Laboratory

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers, and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the federal government as needed to improve efficiency in technical operations and cooperates with academia in the development and use of measurement methods and scientific data.

EEEL consists of five programmatic Divisions and two matrix-managed Offices:

- Electricity Division
- Semiconductor Electronics Division
- Radio-Frequency Technology Division
- Electromagnetic Technology Division
- Optoelectronics Division
- Office of Microelectronic Programs
- Office of Law Enforcement Standards

This document describes the technical programs of the Electromagnetic Technology Division. Similar documents describing the other Divisions and Offices are available. Contact NIST/EEEL, 100 Bureau Drive, Gaithersburg, MD 20899-8100; (301) 975-2220; www.eeel.nist.gov

The cover of this report illustrates the three primary areas of the Electromagnetic Technology Division’s work: metrological applications of cold electronics (NIST-fabricated AC voltage standard chip, upper right), metrology for magnetic data storage (disk drive with its cover removed, lower left), and metrology for the superconductor industry (magnetic resonance imaging system used in medical diagnostics, background image).

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U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

Technology Administration
Cheryl L. Shavers, Under Secretary for Technology

National Institute of Standards and Technology
Raymond G. Kammer, Director

Contents

Welcome

The roughly sixty staff and visitors in the Electromagnetic Technology Division and I take great pride in bringing you this brief report on recent progress of our Division. We have a long history of inventing and providing new standards and measurement technology. We focus on electrical standards and magnetic data storage. This book will tell you more about our current successes.

We began about thirty years ago to bring the unique capabilities of superconducting technology to bear on metrology, the science of measurement. Since that time we have added support for the superconductivity industry and, more recently, the magnetic data storage industry. It has always been our goal to provide U.S. industry with the best metrology in the world. We developed what has become the world's standard of voltage, based on integrated circuits containing tens of thousands of superconducting Josephson junctions, made in our own fabrication facility. We demonstrated the first capacitance standard based on counting of single electrons. For materials analysis, we perfected an X-ray spectrometer that combines the best features of two types of existing detectors and promises to be critical in defect analysis of future semiconductor devices. Our staff leads the international effort to develop standards for superconductors. In magnetics, our staff, along with an industry consortium, ran the first interlaboratory comparison of measurements on magnetic thin films that are the basis of read heads in the disk drive industry. We have developed new techniques to measure magnetic switching speed for both recording heads and media.

This year, NIST's director, Ray Kammer, dedicated improved clean room facilities, which are critical to almost all our efforts and enable us to produce structures smaller than 100 nanometers.

Whether you are our customer and use the results of our efforts, or are simply interested in the remarkable progress our technology brings to measurements, we hope you will find this report exciting. You will read descriptions of our work from fall 1998 through fall 1999, lists of our recent publications, and descriptions of our postdoctoral research opportunities. For the most recent information, please visit our Web site, emtech.boulder.nist.gov

Thanks for your interest in NIST's Electromagnetic Technology Division.

Richard E. Harris
Division Chief

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Fields of Technology

The Electromagnetic Technology Division serves primarily three areas of technology. For the most recent information, please visit our Web site, emtech.boulder.nist.gov

Metrological Applications of Cold Electronics

Using custom integrated circuitry, the Division produces electronic instruments that operate at temperatures close to absolute zero. We use the quantum effects and reduced thermal noise of these circuits to construct metrological tools and standards having performance that would be otherwise impossible to achieve. Examples include 32 000 Josephson junction voltage standards, a prototype capacitance standard based on counting of individual electrons, a microcalorimeter-based X-ray detector having unprecedented energy resolution, and detectors of electromagnetic radiation using lithographed microantennas.

Metrology for the Superconductor Industry

The Division maintains facilities for measuring the critical current of superconducting wire up to several thousand amperes. These facilities are of special use to the industry because of the unique expertise of the Division staff in making these DC measurements. The Division also provides expertise in measuring AC losses in superconductors. Other facilities provide data to the industry on the effects of mechanical strain on superconductor wires. These data provide essential information for designers of superconducting magnets such as those commonly used in magnetic resonance imaging systems for the health care industry, in accelerators for high energy physics, in experimental fusion reactors, and in future applications such as generators, transmission lines, and magnetically levitated trains.

Metrology for Magnetic Data Storage

The Division provides measurement tools for the competitive magnetic data storage industry. We develop measurement tools for rapidly approaching new technology including ultra-high speed recording of ultra-small bits. Both fast electrical and high spatial resolution imaging techniques are explored. In close collaboration with industry trade organizations, we are developing calibration and measurement standards for magnetic thin films commonly used in recording.

Magnetic Recording Metrology

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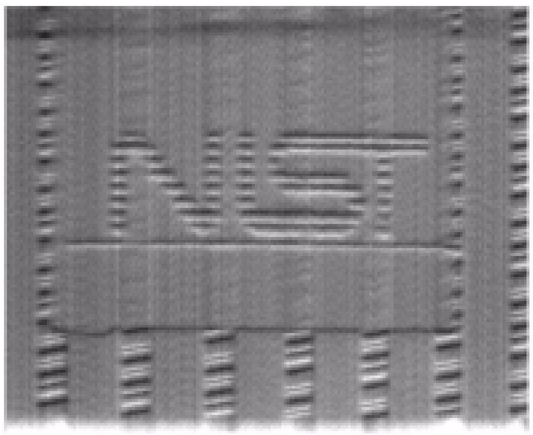
Project Goals

Develop metrology for magnetic data storage media and sensors for industry, instrument manufacturers, and other government agencies.



Hard disk drive data from NIST's magnetic imaging reference sample (MIRS) with the NIST logo overwritten using a hard disk drive head, 100 micrometers _ 100 micrometers scan.

Customer Needs

Magnetic data storage has been a growing industry for several decades. With the widespread use of computers and mass media around the world, it is expected to continue to grow for the foreseeable future. A wide range of products comprise data storage, including audio and video products in various formats (standard and micro-cassettes, digital audio tape, VHS videotape), removable data storage (tapes, floppy disks, read/write compact disks), and non-removable data storage (hard disk drives).

For this wide range of products, there is a wide range of customers for magnetic recording metrology. The hard disk drive industry represents the cutting edge of technology in this area. It is highly competitive in terms of scientific development. In addition, forensic analysis is constantly battling to keep up with the combined effects of increased usage of magnetic recording and the improved technology that allows higher densities.

Technical Strategy

We use a three-pronged approach. This includes development of standards for immediate metrology needs, imaging with advanced magnetoresistive heads for forensic analysis and medium-term metrology development, and *in situ* surface magnetometry for long term metrology needs and scientific research.

In order to respond to short term demands of the data storage industry, two magnetometer reference materials are being developed in collaboration with magnetic instrument manufacturers. These are a magnetic flux standard and a zero-coercivity permeability standard. The metrology is specifically targeted at quality control of magnetoresistive heads, arguably the most critical element in hard drive technology.

The magnetic flux standards are thin film, planar solenoids fabricated using lithographic techniques. Electric currents follow well defined paths in the solenoid, producing a magnetic flux that is traceable to fundamental quantities. This approach is superior to magnetic material standards because it avoids materials issues such as defects and magnetic domains, while still mimicking the macroscopic field of a magnetic thin film. The target flux for the present generation of standards is 1 nanoweber, which is equivalent to approximately 10 nanometers of Permalloy on a 7.6 centimeter wafer. Permalloy is a class of Fe-Ni alloys that is magnetically very soft, with low remanent magnetization.

We will certify prototype, active flux reference specimens for induction-field loopers, traceable to fundamental quantitites of current and geometry.

The zero-coercivity permeability reference standard will be used for quality control of Permalloy films. Since magnetometers are susceptible to coercivity artifacts produced by eddy currents, we will use paramagnetic materials that have no remanent magnetization and support negligible eddy currents.

We will fabricate and characterize thin films and plates of paramagnetic Tb for use in induction-field loopers. We will measure zero crossings of the magnetic response for use as a comparison standard.

Recognizing the importance of magnetic data storage, NIST initiated a 5 year program in 1996 to develop competence in the area of metrology for magnetic storage. This program has resulted in advanced measurement techniques for imaging information stored on magnetic media with high resolution and relative ease. The Nanoscale Recording System (NRS), developed under this initiative, is a general purpose system that uses read/write heads similar to those in computer hard disk drives or tape drives to image and modify data written on magnetic media. The nanoscale recording system can image either by rastering, with computer controlled micrometers, the heads or the media with a piezoelectric *x-y* stage with 1 nanometer resolution. The NRS is being used as a prototype for forensic analysis of audio tapes. We have shown that high speed imaging of specimens can be accomplished, and the signatures of erase heads and write heads have been identified on test materials. In addition, the fields from individual wires in integrated circuits have been measured and characterized using magnetoresistive elements. This opens the way for development of noninvasive probes in the areas of failure analysis and low level chip testing.

We will transfer technology for second harmonic magneto-resistive imaging to industry.

Long-term basic research is being conducted in the area of surface and interface magnetism. This area is important for development of metrology relevant to advanced devices (such as giant magnetoresistive heads and tunnel junctions) and media (such as perpendicular media). In our surface science laboratory we use spin-resolved electron spectroscopy as a magnetometer and for electronic band structure characterization. All three components of spin polarization are analyzed, allowing us to study any type of media. Since the electrons are sensitive to the first few atomic layers of the surface, it allows us to map the magnetization effects that are relevant to advanced devices that use giant magnetoresistive or tunneling effects.

We will connect reorientation transitions in rare-earth/transition-metal structures to the theory of phase transitions. We will measure critical exponents of bulk and surface magnetism in rare-earth films.

Accomplishments

■ Interlaboratory Comparison on Thin Films — We conducted an interlaboratory comparison of the magnetic properties of thin film specimens similar to those used in hard disk drive heads. In collaboration with the National Storage Industry Consortium, nine specimens of various sizes and film thicknesses were sent to industrial, academic, government, and instrument manufacturer laboratories to help identify needs for reference materials. We also participated in a similar pilot study for materials used in hard disk drive media conducted by the International Disk Drive Equipment and Materials Association. The participants all agreed that certified standard reference materials (SRMs) of specific dimensions would have a significant impact on yields and profitability.

■ New Process for Solenoid Flux Standards —A process for fabricating thin film solenoid flux standards was developed in our cleanroom. This involved fabricating two layers of Cu wires, separated by an insulating polyimide layer, with via conductors between the two layers. Special lithographic features were incorporated for accurate determination of the solenoid dimensions, such as the Cu and polyimide layer thicknesses. The first flux prototypes have been completed and tests are underway.

■ Standards Development — We used mathematical models to show that field accuracy of better than 1 percent is feasible in a 1 nanoweber magnetic flux standard. The models showed that the flux was relatively insensitive to typical errors in solenoid positioning in the magnetometer. It was found that Tb-based paramagnetic specimens would satisfy the requirements of a zero-coercivity permeability standard. The key material properties are a high paramagnetic permeability, high chemical purity, and low electrical conductivity. The target flux for the present standard is10 milliwebers per tesla, while producing less than 1 picoweber in remanence due to eddy current artifacts in a 0.02 tesla field. Tests on the first prototype zero-coercivity reference standard are underway.

■ Two-Step Reorientation Transition in Fe — Our surface studies of ultrathin Fe layers on a thin Gd (0001) surface showed that this system has a two-step reorientation transition as temperature is increased. At low temperatures, the Fe remains in-plane, antiferromagnetically coupled to the Gd. At intermediate temperatures, the Fe/Gd surface undergoes a continuous rotation to a canted direction. Because the exchange coupling in Gd is small, and domain walls are narrow, we expect an inhomogeneous magnetization depth profile in the Gd thin films in this intermediate temperature range. Available models in ultrathin films assume a homogeneous magnetization and exclude the coexistence of continuous and discontinuous behavior within one 90 degree reorientation. This shows that the inclusion of a magnetization depth profile is probably necessary to reveal the underlying physics in this system.

Recent Publications

C. S. Arnold, D. P. Pappas, and A. P. Popov, "MOKE Study of a Two-Step Reorientation Transition of an Ultrathin Magnetic Film," J. Appl. Phys., in press.

C. S. Arnold, D. P. Pappas, and A. P. Popov, "Second and First Order Phase Transitions in the Magnetic Reorientation of Fe/Gd," Phys. Rev. Lett. **83**, 3305-3308 (October 1999).

D. P. Pappas, C. S. Arnold, and A. P. Popov, "Spin Reorientation Phase Transition of Ultrathin Fe Films Grown on Gd(0001)," in *Magnetism and Electronic Correlations in Local-Moment Systems: Rare Earth Elements and Compounds,* M. Donath, P. A. Dowben, and W. Nolting, eds., World Scientific (1999) 141-152

C. S. Arnold, M. Dunlavy, D. Venus, and D. P. Pappas, "Magnetic Susceptibility Analysis of the Relaxation-Time for Domain-Wall Motion in Perpendicularly Magnetized, Ultrathin 1.5 ML Fe/2 ML Ni/W(110) Films," J. Magn. Magn. Mater. **198-199**, 465-467 (June 1999).

C. S. Arnold, D. P. Pappas, and D. Venus, "Domain Formation Near the Reorientation Transition in Perpendicularly Magnetized Ultrathin Fe/Ni Bilayer Films," J. Appl. Phys. **85**, 5054-5059 (April 1999).

Magnetic Instruments and Materials Characterization

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Project Goals

Develop instruments, measurement protocols, and theoretical models to characterize the magnetic properties of films, particles, and bulk solids as functions of magnetic field strength, field history, temperature, and time. Develop, promote, and transfer to industry magnetic metrology for applications in magnetic data storage, magneto-optics, magnetochemistry, power conversion, and high frequency electromagnetics.

Unique high voltage, fast risetime pulse generators used in the project's magnetic switching studies are designed and built by electrical engineer Tony Kos. He also designs interfaces for computer control and data acquisition for the project's experiments.

Customer Needs

Researchers, developers, producers, and users of magnetic materials need tools for the accurate determination of magnetic properties and the analytical interpretation of data. This project focuses on the development of new measurement methods and protocols. It supports research and development efforts principally in the magnetic data storage industry: inductive recording heads, magnetoresistive read-back heads, thin-film and particulate recording media, and magnetic random-access memories. Additionally, the project develops magnetic sensors, sensor arrays, and nanostructures for metrology applications and standards. It collaborates with companies, other government agencies, and universities that need magnetic measurements for materials characterization.

Technical Strategy

The primary focus of this project is the measurement of switching time of magnetic materials and devices for applications in data storage. This has led to the development of cutting-edge instrumentation and experiments using magneto-optics and microwave circuits. Microwave coplanar waveguides are used to deliver magnetic field pulses to devices under test. In response, the specimen magnetization switches — but not smoothly. Rather, the magnetization vector undergoes precession, much as a spinning top precesses in the Earth's gravitational field. Sometimes, the magnetization can precess nonuniformly, resulting in the generation of spin waves or, in the case of small devices, incoherent rotation.

We use several methods to detect the state of magnetization as a function of time. These include …

- … The magneto-optic Kerr effect (MOKE), which makes use of the rotation of polarization of light upon reflection from a magnetized film. We have used MOKE to measure equilibrium and nonequilibrium decay of magnetization in recording media.
- … Second-harmonic magneto-optic Kerr effect (SHMOKE), which is especially sensitive to surface and interface magnetization. We have used SHMOKE for time-resolved, vectorial measurements of magnetization dynamics and to demonstrate the coherent control of magnetization precession.
- … A microwave inductive technique, in which the changing magnetic state of a specimen is deduced from the change in inductance of a waveguide. This technique is fast, inexpensive, and easily transferable to industry. It may also be used as a time-domain permeameter to characterize magnetic materials.
- … Measurements and modeling of sub-nanosecond switching in actual, giant magnetoresistance (GMR), multilayer, "spin-valve" nano-devices. Coplanar waveguides and magnetic specimens and devices for testing are prepared using sputtering deposition and are patterned in the Division's cleanroom. Micromagnetic modeling provides important insight into the physical processes we measure.

Our technical strategy is to identify future needs in the data-storage and other important industries, develop new metrology tools, do the experiments and modeling to provide data and theoretical underpinnings, and try to make significant

Your experiments on very fast switching in magnetic films … are well designed and incisive. [They are] exactly the right kind of experiments that should be done at an institution like NIST. It advances the science of metrology, and requires facilities, both human and economic, which will coexist in no other kind of institution.

Prof. Robert L. White
Director
Center for Research on Information Storage Materials Stanford University

contributions. We work in three main areas: time-resolved magnetodynamic measurements, metrology for magneto-electronics, and magnetic instruments and measurements of electromagnetic materials.

Time-Resolved Magnetodynamic Measurements

We concentrate on two major problems in the magnetic data storage industry: (1) data rate, the problem of gyromagnetic effects, and the need for large damping without resorting to high fields; and (2) storage density and the problem of thermally activated magnetization reversal.

Data transfer rates are increasing at 40 percent per year (30 percent from improved linear bit density and 10 percent from greater disk rotation speed). The maximum data transfer rate is currently 50 megabytes per second. In 5 years, frequencies for writing and reading will be in the microwave region, which begs the question, "How fast can magnetic materials switch?"

We will develop time-resolved, second-harmonic magneto-optic Kerr effect measurements (TRe-SHMOKE) to include two-dimensional scanning. We will measure the spatial decay of magnetic excitations as a function of distance from the waveguide field source. Using overcoats of various metals and thicknesses, we will investigate possible SHMOKE enhancement due to plasmon effects.

We will design and build a time-resolved MOKE system using a diode laser for time-resolved, generalized, magneto-optic ellipsometry (TRe-GME). Results will be compared with vectorial TRe-SHMOKE. We will measure the dynamics in multilayers and patterned arrays of Permalloy.

In collaboration with the National Storage Industry Consortium and the NIST Radio-Frequency Technology Division, we will develop a high bandwidth, inductive current probe for recording heads. The task will involve a proof of concept, design of the probe pattern, and test of the probe on Permalloy inductive specimens. We will integrate the current probe with a commercial recording head assembly.

The current laboratory demonstration record for storage density, which will be superceded by the time this report is published, is 5.5 gigabits per square centimeter (35 gigabits per square inch). How much farther can longitudinal media (with in-plane magnetization) be pushed? Can perpendicular recording or discrete data bits extend magnetic recording beyond the superparamagnetic limit at which magnetization becomes thermally unstable?

We will characterize commercial magnetic recording media on waveguides distributed to industrial collaborators. We will improve pulsed media measurement techniques by optimizing NIST pulse generators and fabricating narrower waveguides with thinner planarization layers. We will study the physics of media reversal and the effect of varying field risetime on media switching speed and coercivity.

We will develop models and micromagnetic code to understand the dynamics of complex systems, including the dynamics of films with magnetization ripple. We will develop a theory for generalized second-harmonic magneto-optic Kerr ellipsometry (Gen-SHMOKE).

Metrology for Magnetoelectronics

Magnetic random access memories (MRAM) have the potential to be as fast or faster than semiconductor computer memories, with the additional advantage of being nonvolatile. MRAM elements are very similar to the GMR "spin-valve" and magnetic tunnel junction designs currently used in advanced read heads for hard disk drives. As with heads, switching speeds are an important consideration. We have fabricated prototype MRAM arrays and instrumented them for switching experiments.

We will perform high speed measurements of magnetic GMR device dynamics and switching. In particular, we will measure and model the switching probabilities of small spin-valve devices as a function of pulse width, pulse amplitude, and temperature. The results will explain the observation of metastable states and non-monotonic switching probabilities. We will determine the effect of disorder on high speed rotation of spin-valve sensors by comparing experimental data with simulations.

We will develop a prototype high bandwidth GMR device for sensing high-speed circuit operation and head write fields.

We are investigating sub-micrometer GMR and magnetic tunneling devices for use in advanced recording read-head sensors. It will be essential for these devices to operate at frequencies above 1 gigahertz and that the micromagnetic dynamical behavior be well understood. We will measure the fundamental frequency limits of these sensors and perform rigorous tests of the best micromagnetic models to determine if they are adequate to determine device performance at gigahertz frequencies and nanometer sizes.

We will fabricate and measure the dynamical response of sub-micrometer magnetic tunnel junction devices.

We will fabricate specimens and make in-situ current-in-plane magnetoresistance

(CIP-GMR) measurements. Our aim is to improve our fabrication process to be able to match the best values of magnetoresistance reported in the literature.

New methods to measure spin-dependent transport in thin films and at interfaces are required for the development of advanced spin-electronic technologies. These technologies include not only recording heads and MRAM, but also spin-dependent transistors, spin-polarized light-emitting diodes, and magnetic cellular automata. We will develop novel methods for measuring spin transport in thin films and at thin-film interfaces, including in-situ conductance and magnetoconductance measurements of thin-film multilayers.

We will study electron scattering at surfaces and interfaces in GMR spin-valves. In particular, we will measure the amount of specular scattering created by noble-metal and surface-oxide overlayers. We will develop a physical interpretation of CIP-GMR. We will determine the fraction of spin-dependent scattering created at interfaces versus the bulk in typical structures in the Co/Cu, NiFe/Cu, and possibly the Fe/Cr systems. We will manipulate specular scattering in epitaxial GMR spin-valves through microstructural control, and provide the first estimate of sensitivity of GMR to surface reflectivity.

We will demonstrate in-situ magneto-conductance measurement as a probe of interface quality and surface segregation through systematic control of Co/Cu intermixing. We will explore the possibility of attaining the highest values of spin-valve GMR through interface engineering. We hope to provide in-situ conductance standards to magnetic industry as a process diagnostic for GMR spin valve deposition.

In the past decade, magnetic force microscopy has become an important tool for measuring magnetic structures on a sub-micrometer scale. In 1999, the recording industry announced a high-density recording demonstration with magnetic structure at the current resolution limits of MFM. A critical need exists for improved resolution of magnetic imaging techniques and for the development of standards to measure magnetic imaging resolution. The Division has created magnetic imaging reference standards (MIRS), characterized by both MFM and scanning electron microscopy with polarization analysis (SEMPA), for use in calibrating MFMs. This year, we will continue our calibration efforts using well characterized magnetic nanostructures.

We will make quantitative comparisons of MFM images of CoPt nanodots and calculated images. We will determine if CoPt nanostructures can provide a better resolution standard than the current MIRS specimens. We will improve our microfabrication technique to allow routine fabrication of sub-50 nanometer magnetic structures.

Magnetic Instruments and Measurements of Electromagnetic Materials

The project helps industry, government, and university labs with some of their more difficult electromagnetic measurement needs. We have a record of providing accurate, impartial measurements.

We will develop a robust, pulsed, inductive microwave magnetometer (PIMM) system for the rapid measurements of thin-film specimens. We will develop a differential technique for inductive measurements to facilitate the use of large field pulses.

We will complete electrical resistivity measurements of carbon and aluminum fibers for defense applications. We will continue our measurements of the properties of magnetic nanoparticles and thin films. We will measure the magnetization of nickel-metal hydrides for battery and fuel cell applications. We will measure magnetic hysteresis losses in multifilamentary superconductors for fusion and high energy physics applications, and contribute to international standards efforts. We will recalibrate the magnetic instruments in our project.

Accomplishments

- First Observation of Transient Spin Waves in Magnetic Films — Using a new technique of vectorial second-harmonic magneto-optic Kerr effect, we detected the transient generation of spin waves during magnetic field step excitations in Permalloy (Ni-Fe) films. The effect manifests itself as a 50 percent reduction in average magnetization during the first few nanoseconds of dynamical magnetization response. This is the first time that experimental measurements have shown that coherent magnetization response to an applied field pulse can result in efficient spin wave generation.

A key aspect of the experiment is to create a highly rippled magnetization state in the specimen through the application of a bias field orthogonal to the preferred anisotropy axis. When the bias field is equal to the anisotropy field, the magnetization falls into a relaxed state that is highly susceptible to spatial variations in the anisotropy, resulting in magnetization ripple. The ripple state acts to nucleate the spin waves in response to an applied field pulse, much as vortex generators on the leading edges of commercial aircraft wings induce turbulent airflow along the wing surface, preventing stall at low air velocities. This discovery will lead to further understanding of the fundamental limits of high speed switching in data storage devices and how nonuniformities in anisotropy can adversely affect device performance. Further work will address how to control spin wave generation in response to the application of pulsed magnetic fields.

■ Switching in Sub-Micrometer Devices on Sub-Nanosecond Time Scales — We completed a study of high speed switching in spin valves 0.5 to 0.8 micrometers wide. These devices are similar to those being developed for giant magnetoresistive (GMR) read heads and magnetic random access memory (MRAM) elements for data storage. The devices were repeatedly switched with pulses whose widths ranged from 0.2 to 2 nanoseconds. While the low frequency characterization showed that the devices were bistable, many of the devices actually exhibited long-lived metastable states when driven by fast magnetic field pulses. Micromagnetic simulations indicate that the devices should be reversing by domain wall motion for the low amplitude pulses and by magnetization rotation for the large field pulses. The simulations, at present, do not predict the existence of long-lived metastable states or an observed oscillation of the switching probability.

The data suggest that there are given field ranges where different reversal mechanisms are efficiently driven. If the system is overdriven, it can get stuck in a metastable state that is accessible only by the large transient energy that is available during high speed switching. This work is one of the first to analyze the details of dynamical switching in sub-micrometer devices on sub-nanosecond time scales. The results are important for the development of MRAM, where reproducible switching of 1 billion sub-micrometer elements will be required, and of magnetic read heads, where the dynamical studies provide a much more rigorous test of the accuracy of micromagnetic simulations.

■ Relaxation Times for Magnetization Reversal in Recording Media — We measured sub-nanosecond switching speeds in high coercivity Co-Cr-Ta recording media. The fast reversal of the media was correlated with magneto-optical image analyses showing that the media had very short magnetic correlation lengths. Such results indicate that an advanced recording medium that is magnetically decoupled may also have fast magnetization reversal. This result contrasts with our earlier measurements on other media that had slow switching times of about 5 nanoseconds and long correlation lengths on the order of a few micrometers. These results point to a picture of magnetization reversal via magnetostatically driven correlations.

■ Inductive Measurement System Used to Measure Frequency Dependence of Permeability — We obtained the frequency dependence of permeability from the inductive time response signal of films on coplanar waveguides. Because the measured inductive signal is proportional to the time derivative of the magnetization response to a step-function drive field, the Fourier transformation of the measured time response represents the frequency dependence of the complex susceptibility. By dividing the complex susceptibility into its real and imaginary parts, one can obtain the frequency dependence of the permeability of a thin magnetic film. The technique is simple, and only the applied external bias field limits the frequency response because it determines the resonance frequency. For typical bias fields of several hundred amperes per meter, a frequency response of up to several gigahertz can be obtained. The technique does not require a special coil set or special yoke design. Simple coplanar waveguides with a wide-band sampling oscilloscope are used. The calibration and application of the technique is much simpler and has a higher bandwidth than other permeameters. Comparisons with traditional measurements show excellent agreement.

■ Coherent Control of Magnetization Precession — Last fiscal year, we demonstrated the ability to coherently control precessional dynamics in thin NiFe films. By using two field pulses with an adjustable delay between them, the underdamped precessional ringing normally present in thin Ni-Fe was eliminated by moving the delay such that two out-of-phase precessions were created. Destructive interference canceled the magnetization precession. Precessional effects in recording heads may result in deleterious nonlinear transition shifts in disk drive systems. We performed further coherent control experiments this year and compared the results to theory.

Standard Reference Materials

■ Magnetic Imaging Reference Sample (MIRS), Cat. No. 8088, 24 delivered to Standard Reference Materials Program.

Collaborations

- National Storage Industry Consortium, San Diego, inductive current probe for recording heads.
- International Business Machines, Almaden Research Center, San Jose, switching in magnetic recording media.
- Center for Magnetic Recording Research, University of California, San Diego, modeling of magnetic switching.
- Center for Materials for Information Technology, University of Alabama, Tuscaloosa, high frequency permeability measurements.
- Colorado Center for Information Storage, University of Colorado, Boulder, guest lecturers.
- Department of Physics, University of Colorado, Boulder, magnetic switching.
- Department of Physics, University of Colorado, Colorado Springs, exchange coupled magnetic bilayers.
- Department of Metallurgical and Materials Engineering, Colorado School of Mines, Golden, magnetization of metal hydrides.

Standards Committee Participation

- Ron Goldfarb participates in standards committees A-6 (Magnetic Properties) and E-43 (Metric Practice) of the American Society for Testing and Materials (ASTM).

External Recognition

- Tom Silva has been selected to be an IEEE Magnetics Society Distinguished Lecturer for 2000-2001.
- Ron Goldfarb serves as Editor-in-Chief of the *IEEE Transactions on Magnetics,* an archival journal of the Institute of Electrical and Electronics Engineers.

Recent Publications

S. Kaka and S. E. Russek, "Switching in Spin-Valve Devices Subjected to Fast Longitudinal Magnetic Field Pulses," submitted.

S. E. Russek, S. Kaka, and M. J. Donahue, "High-speed Dynamics, Damping, and Energy Relaxation Times in Submicrometer Spin-Valve Devices," submitted.

T. J. Silva, P. Kabos, and C. Alexander, Jr., "Direct Observation of Transient Spin-Wave Excitation in a Ferromagnetic Film Using the Second-Harmonic Magneto-Optic Kerr Effect," submitted.

J. Moreland, M. Löhndorf, P. Kabos, and R. D. McMichael, "Ferromagnetic Resonance Spectroscopy with a Micromechanical Calorimeter Sensor," submitted.

M. Löhndorf, J. Moreland, and P. Kabos, Ferromagnetic Resonance Detection with a Torsion-Mode Atomic Force Microscope," Appl. Phys. Lett., in press.

P. Kabos, A. B. Kos, and T. J. Silva, "Vectorial Second-Harmonic Magneto-Optic Kerr Effect Measurements," J. Appl. Phys., in press.

N. D. Rizzo, T. J. Silva, and A. B. Kos, "Relaxation Times for Magnetization Reversal in a High Coercivity Magnetic Thin Film," Phys. Rev. Lett., in press.

N. D. Rizzo, T. J. Silva, and A. B. Kos, "Nanosecond Magnetization Reversal in High Coercivity Thin Films," IEEE Trans. Magn., in press.

M. Löhndorf, J. Moreland, P. Kabos, and N. Rizzo, "Microcantilever Torque Magnetometry of Thin Magnetic Films," J. Appl. Phys., in press.

Z. Celinski, D. Lucic, N. Cramer, R. E. Camley, R. B. Goldfarb, and R. B. Skrzypek, "Exchange Biasing in Ferromagnet/Antiferromagnet Fe/$KMnF_3$," J. Magn. Magn. Mater. **202**, 480-484 (August 1999).

S. E. Russek, J. O. Oti, and Y. K. Kim, "Switching Characteristics of Spin Valve Devices Designed for MRAM Applications," J. Magn. Magn. Mater. **198-199**, 6-8 (July 1999).

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T. M. Crawford, T. J. Silva, C. W. Teplin, and C. T. Rogers, "Subnanosecond Magnetization Dynamics Measured by the Second-Harmonic Magneto-Optic Kerr Effect," App. Phys. Lett. **74**, 3386-3388 (May 1999).

S. E. Russek, T. M. Crawford, and T. J. Silva, "Study of NiFe/Al/Al_2O_3 Magnetic Tunnel Junction Interfaces Using Second-Harmonic Magneto-Optic Kerr Effect," J. Appl. Phys. **85**, 5273-5275 (April 1999).

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Nanoprobe Imaging for Magnetic Technology

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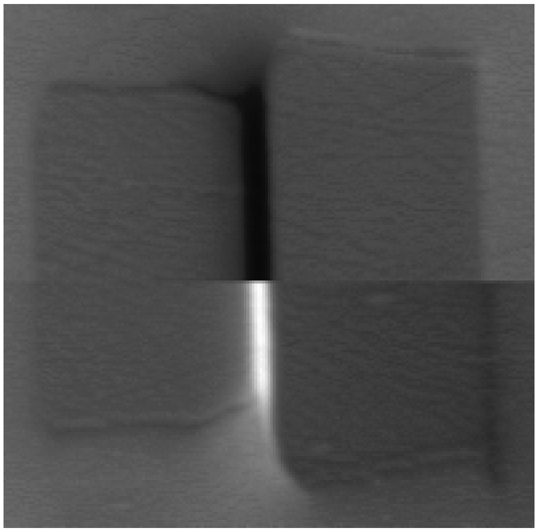
Project Goals

Develop scanned probe microscopy (SPM) in support of the data storage industry, with an emphasis on instrumentation for routine, high resolution imaging. Work with industry to understand and relate SPM images to magnetic and electronic properties of current and future media and devices for the recording industry.



Magnetic force microscopy (MFM) image of the air bearing surface of a hard disk recording head. During the raster scan, the current in the head is reversed. This leads to the shift from light to dark contrast near the gap between the pole tips in the MFM image made using a high magnetic coercivity tip coating. We are collaborating with the University of Nebraska to develop two types of MFM tips: ones with high coercivity coatings that do not switch, and superparamagnetic coatings that switch without hysteresis. Hysteretic tip coatings that switch during MFM imaging of heads can cause unpredictable artifacts.

Customer Needs

The National Storage Industry Consortium (NSIC) recently drafted a recording head metrology roadmap that calls for high resolution, quantitative, magnetic microscopes and magnetometers that go beyond current technology limitations. Magnetic measurement systems have become increasingly complex. NIST helps move instruments from the development stage to routine operation in the development lab and on the factory floor. In particular, the Electromagnetic Technology Division has expertise in magnetism, probe microscopy, and cleanroom microfabrication. Industry also looks to NIST for measurements in magnetism traceable to fundamental quantities as it pushes into new scales of time and length.

Technical Strategy

In order to improve upon magnetic force microscopy and keep pace with industry, we are focusing on specialized magnetic force microscopy (MFM) tips for imaging heads and media. We are developing ultra-small tips for 10 nanometer magnetic image resolution. We are looking at new technologies for controlling nanoscale magnetic structure near the probe tip and for making sharp tips. In addition, we are developing more sensitive MFM instruments.

Quantitative field mapping of heads and media can be done with tiny field probes based on electromechanical detection of magnetic resonance. We are developing ways to attach sub-micrometer magnetic resonance particles to ultra-sensitive cantilevers and to position particles a few nanometers from the specimen surface.

We are developing new tools for measuring nanoscale magnetic phenomena and devices based on fundamental quantities for next-generation data storage. This includes microelectromechanical (MEMS) magnetometers that offer tremendous magnetic moment sensitivity for a specimen integrated with the magnetometer. Currently, we are broadening cleanroom fabrication capabilities to include MEMS bulk and surface micromachining of Si.

We will bring our new micromachining facility on-line. We will fabricate high performance micromachined magnetometer probes for 20 nanometer MFM resolution. These improvements in MFM will keep pace with industry needs.

We will fabricate fully integrated MEMS magnetometers. We will develop a magnetic resonance spectrometer on a chip. We will achieve 1 nanometer magnetic resonance imaging resolution of thin film ferromagnetic specimens. We will provide industry with new, cost effective measurement systems that are calibrated at the nanometer scale.

We will develop atomic-scale magnetic instrumentation for the visualization of fundamental magnetic phenomena.

Accomplishments

- Feasibility of New Scanning-Probe Microscope — We have demonstrated the feasibility of quantitative, high resolution imaging of magnetic fields, such as those encountered in magnetic recording. The technique is based on magnetic resonance force microscopy (MRFM), a technology recently developed in several laboratories in the U.S. and abroad. High resolution field mapping with an MRFM instrument relies on a small magnetic resonance particle mounted on an atomic force cantilever, which constitutes a very sensitive probe of local magnetic fields near a magnetic device. Magnetic resonance phenomena are the basis for the most accurate measurements of magnetic fields.

■ New Ferromagnetic Resonance Spectrometer — We developed a new ferromagnetic resonance (FMR) spectrometer based on a micromechanical calorimeter sensor for measurements of thin film magnetic specimens. The sensor is an atomic force microscope cantilever coated with a ferromagnetic thin film that serves as a bimaterial thermal sensor to measure absorption of microwaves. Spectra show a peak in the cantilever deflection, as a function of applied magnetic field, which corresponds to a peak in the absorbed microwave power under FMR conditions for the ferromagnetic film. The technique is a potentially superior way to make quantitative measurements of the saturation magnetization of thin-film specimens with very small magnetic moments.

Recent Publications

J. Moreland, M. Löhndorf, P. Kabos, and R. D. McMichael, “Ferromagnetic Resonance Spectroscopy with a Micromechanical Calorimeter Sensor,” submitted.

M. Löhndorf, J. Moreland, and P. Kabos, “Ferromagnetic Resonance Detection with a Torsion-Mode Atomic Force Microscope,” Appl. Phys. Lett., in press.

M. Löhndorf, John Moreland, P. Kabos, and N. Rizzo, “Microcantilever Torque Magnetometry of Thin Magnetic Films,” J. Appl. Phys., in press.

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Superconductor Standards and Technology

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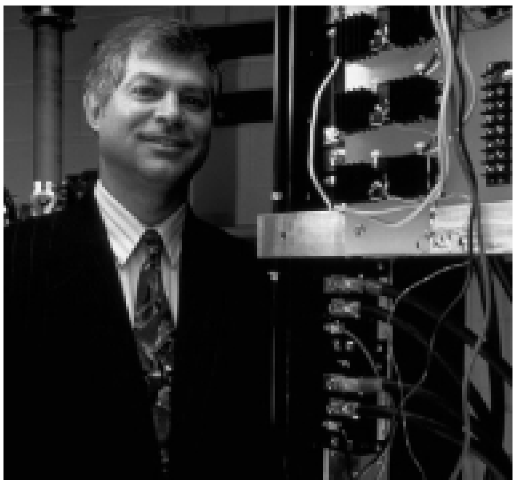
Project Goals

Provide standards, measurement techniques, quality assurance, and reference data for both high temperature and low temperature superconducting wire technology. Support industries in magnetic resonance imaging, laboratory magnets, fault current limiters, magnetic energy storage devices, motors, generators, and transmission lines. Oversee international standards in the entire field of superconductivity, including both large scale and electronic applications.



Loren Goodrich represents the U.S. on the International Electrotechnical Commission's Technical Committee 90 on superconductivity.

Customer Needs

We serve the U.S. superconductor industry, which consists of many small companies with limited resources available to commit to the development of new metrology and standards. We participate in projects sponsored by other government agencies that involve U.S. industry, universities, and national laboratories.

The potential impact of superconductivity makes this technology very important. We are focused on (1) developing the new metrology needed for the evolving large scale superconductor technology, (2) participation in interlaboratory comparisons needed to verify techniques and systems used by U.S. Industry, and (3) developing international standards for superconductivity needed for fair and open competition and improved communication.

Technical Strategy

This project's primary activities are superconducting critical current measurement metrology, interlaboratory comparisons, and development of international standards. One of the most important performance parameters for large scale superconductor applications is the critical current. Critical current is difficult to measure correctly and accurately; thus, these measurements are often subject to scrutiny and debate.

With each significant advancement in superconductor technology, new procedures, interlaboratory comparisons, and standards are needed. International standards for superconductivity are created through the International Electrotechnical Commission (IEC), Technical Committee 90 (TC 90).

The next generation of Nb_3Sn and Nb_3Al wires is pushing towards higher current density, less stabilizer, larger wire diameter, and higher magnetic fields. The resulting higher current required for critical current measurements turns many minor problems into significant engineering challenges. For example, specimen heating from unexpected sources during the measurement can cause a wire to appear to be thermally unstable.

We will determine a procedure for routine measurements of critical current to 2000 amperes at 12 tesla fields.

We will study the effect of extrinsic parameters on overall stability of Nb_3Sn wires during routine testing to 1000 amperes in a magnetic field of 12 teslas.

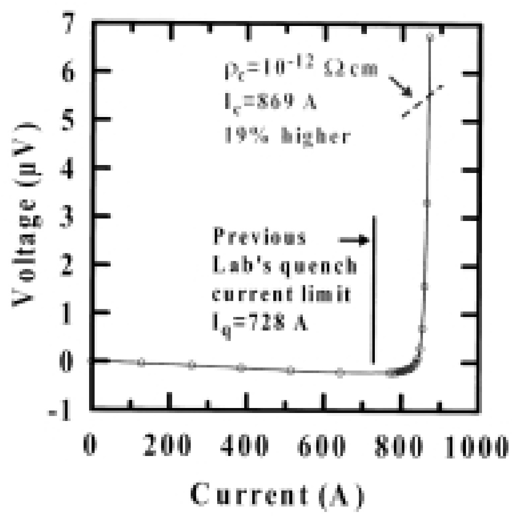
Some of the Nb-Ti wires currently being manufactured for the Large Hadron Collider have critical current specifications of about 2000 amperes at 5 teslas. We have been asked to verify the critical current of some of these wires because we have the measurement capability, which falls between many laboratories' routine wire testing up to 1000 amperes and some laboratories' cable testing up to 20 000 amperes. This type of work helps us become involved in the present measurement issues facing U.S. industry. The experience gained in doing these measurements will help make NIST's future standards more practical.

We will provide customer verifications of Nb-Ti superconductor wire performance.

Accomplishments

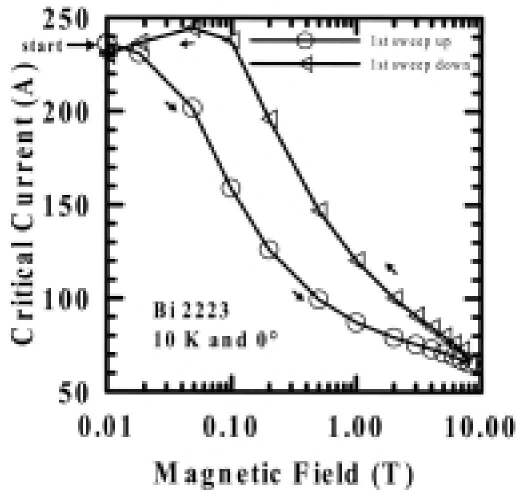
- Interlaboratory Comparison of Critical Current Measurements — We measured critical current of two latest-generation Nb_3Sn conductors. These wires are easily driven into the normal state, thus pushing the limits of conductor stability. Another national laboratory was unable to obtain a critical current value for one of the specimens because the superconductor would quench (go into the normal state) at low currents.

It is extremely important to U.S. superconductor wire manufacturers to know whether their conductors are intrinsically unstable or whether extrinsic factors in the measurement are causing observed instabilities. The critical currents for both specimens were close to 900 amperes at 12 teslas. A plot of the voltage-current characteristic is shown below. It appears that extrinsic factors are significant and new measurement techniques are necessary for some of the less stable conductors.



The voltage-current characteristic of a Nb_3Sn wire in a 12 tesla magnetic field. The slight negative voltage is an artifact of the measurement.

- New Variable-Temperature Measurement of Critical Current — We developed and verified a new variable-temperature critical current measurement system with currents up to 500 amperes. The system includes advances in specimen current supply capability, data acquisition variables, operating conditions, and cryostat design. A comparison of data taken in liquid helium and in flowing helium gas agreed within 0.05 kelvins for currents over 400 amperes. We used this system to measure commercially produced Ag sheathed $Bi_2Sr_2Ca_1Cu_2O_x$ and $Bi_2Sr_2Ca_2Cu_3O_x$ multifilamentary tapes to currents over 250 amperes. The plot shows that the measured critical current of a $Bi_2Sr_2Ca_2Cu_3O_x$ specimen is hysteretic (irreversible) with magnetic field sweeps. The measured critical current is also hysteretic with both angle sweeps and temperature sweeps at constant field.



Critical current as a function of magnetic field sweep for a Ag/ $Bi_2Sr_2Ca_2Cu_3O_x$ tape at 10 kelvins.

- Latest International Standard — We worked extensively on the second international standard on superconductivity, which was published in March 1999 by IEC Technical Committee 90 (TC 90). The document is IEC 61788-2 Superconductivity – Part 2: Critical Current measurement – DC critical current of Nb_3Sn composite superconductors. It is based on the NIST Nb-Ti critical current standard, which we created.

Special Services

- We measured residual resistivity ratio (RRR) of 31 high purity Cu specimens from an aerospace company. The RRR measurements are used to estimate the low temperature thermal conductivity of thermal straps to be used in several instruments for the Space Infrared Telescope Facility.

- We measured critical currents of five Nb-Ti conductors from a U.S. wire manufacturer, which were beyond their measurement capability. The company has an occasional need for some measurements at high current (2000 amperes) or high field (12 teslas). The company considers NIST to be the only available source for measurements at such high currents or fields.

Standards Committee Participation

- Loren Goodrich was the chairman of IEC/TC 90; the U.S. Technical Advisor to TC 90; the

Convener of Working Group 2 (WG2) in TC 90; the primary U.S. Expert to WG4, WG5, and WG6; and the secondary U.S. Expert to WG1, WG3, and WG7.

- Ted Stauffer was Administrator of the U.S. Technical Advisory Group to TC 90.

Recent Publications

L. F. Goodrich "Intercomparison Program in USA Part 1: I_c Comparison," Cryogenics, VAMAS Supplement, submitted

L. F. Goodrich "Intercomparison Program in USA Part 2: Simulator Round Robin Test," Cryogenics, VAMAS Supplement, submitted.

L. F. Goodrich "Critical Current Measurement Methods for Oxide Superconductor Tapes and Wires Part 1: Transport Current Method," Cryogenics, VAMAS Supplement, submitted.

L. F. Goodrich, L. T. Medina, and T. C. Stauffer, "High Critical-Current Measurements in Liquid and Gaseous Helium," Adv. Cryo. Eng. (Materials) **44**, pp.873-880 (November 1998).

"Superconductivity – Part 2: Critical Current Measurement – DC Critical Current of Nb_3Sn Composite Superconductors," International Electrotechnical Commission, International Standard IEC 61788-2 (March 1999).

Superconductor Interfaces and Electrical Transport

Technical Contact:
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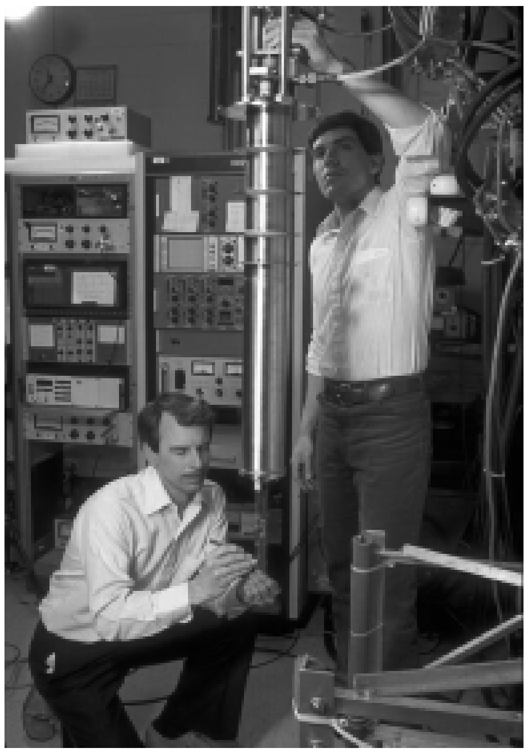
Project Goals

Develop unique measurement capabilities in electromechanical testing for the superconductor industry. Develop an electromechanical data base that will allow the magnet industry to design reliable superconducting magnet systems. Provide the third-party independent status needed by U.S. government agencies to assess superconductor electromechanical performance for wire procurement and research.



Jack Ekin and Steve Bray preparing to measure the electromechanical characteristics of a superconductor.

Customer Needs

Our project serves industry's needs in primarily two areas. First, there is the need to develop a reliable measurement capability in the severe environment of superconductor applications: low temperature, high magnetic field, and high stress. The data are being used, for example, in the design of superconducting magnets for the 2 billion dollar per year magnetic resonance imaging (MRI) industry.

The second area is to provide data and feedback to industry for the development of high performance superconductors. This is an especially exciting area because of the recent deregulation of the electric power utilities and the attendant large effort being devoted to developing reliable superconductors for power conditioning and enhanced power transmission capability. We have received numerous requests, both from industry and from government agencies representing industrial suppliers, for reliable electromechanical data to help guide their research and development effort in this critical growth period.

The recent success of the second generation of high temperature superconductors has brought with it a new set of measurement problems in handling these brittle conductors. We have the expertise and equipment to address these problems.

Technical Strategy

Our project has a long history of unique measurement service in the specialized area of electromechanical metrology. Significant emphasis is placed on an integrated approach. We provide industry with first measurements of new materials, specializing in cost effective testing at currents less than 1000 amperes. Consultation is also contributed to industry on developing their own measurements for routine testing. We also provide metrology consultation to the magnet industry to predict and test the performance of very large cables with capacities on the order of 10 000 amperes, based on our tests at smaller scale. In short, our strategy has consistently been to sustain a small, well connected team approach with industry.

We have developed an array of specialized measurement systems to test the effects of mechanical stress on the electrical performance of superconducting materials. The objective is to simulate the operating conditions to which a superconductor will be subjected in magnet applications. Among these measurement systems are apparatus for measuring the effects of axial tensile stress and transverse compressive stress, and a unique system for determining the electromechanical properties of reinforced superconducting composite coils.

These measurements are an important element of our ongoing work with the U.S. Department of Energy (DOE). The DOE Office of High Energy Physics sponsors our research on electromechanical properties of candidate superconductors for particle accelerator magnets. These materials include low temperature superconductors (Nb_3Sn and Nb_3Al), as well as

measuring the effects of mechanical stress and strain on superconductor performance. … NIST enabled ASC to demonstrate that our Bi-2223 conductor has a transverse compressive stress tolerance greater than 100 megapascals.

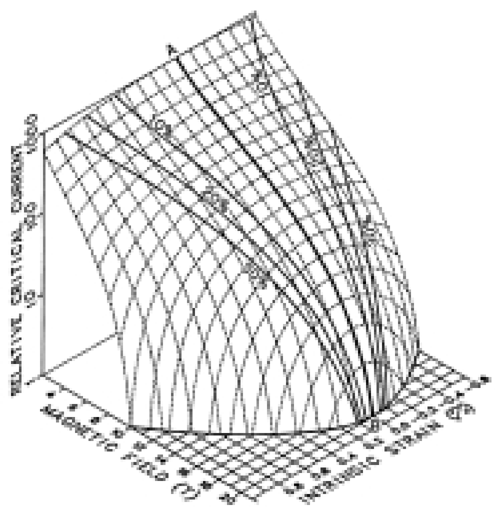
Dr. L. J. Masur
Senor Manager
American Superconductor Corporation

high temperature superconductors (Bi-Sr-Ca-Cu-O and Y-Ba-Cu-O). The purpose of the database produced from these measurements is to allow the magnet industry to design reliable superconducting magnet systems.

We will develop fatigue apparatus and obtain the first measurements of the effect of cyclic transverse stress on the critical current of $Bi_2Sr_2Ca_2Cu_3O_x$.

Some of our research is sponsored in part by the DOE Office of Energy Efficiency and Renewable Energy. Here we focus on high temperature superconductors for power applications, including transformers, power conditioning systems, motors and generators, superconducting magnetic energy storage (SMES), and transmission lines. In all these applications, the electromechanical properties of these inherently brittle materials play an important role in determining their successful utilization.

We will complete the first statistically significant set of measurements of transverse stress effects in Y-Ba-Cu-O-coated superconductors.



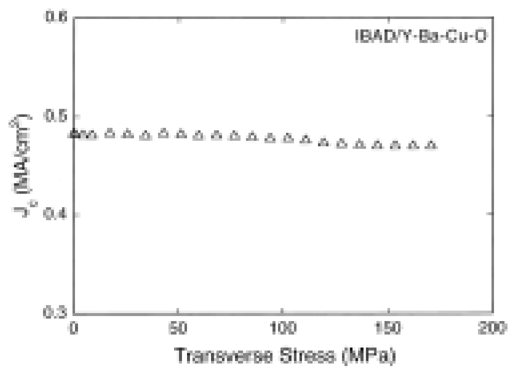
Critical current-field-strain surface for the A-15 superconductor Nb_3Sn at 4 kelvins.

In the area of low temperature superconductors, we have embarked on a fundamental program to generalize the Strain Scaling Law (SSL), a magnet design relationship we discovered more than a decade ago. Since then, the SSL has been used in the structural design of most large magnets based on superconductors with the A-15 crystal structure. However, this relationship is a one-dimensional law, whereas magnet design is three dimensional. Current practice is to generalize the SSL by assuming that distortional strain, rather than hydrostatic strain, dominates the effect. Recent measurements in our laboratory suggest that this assumption is invalid. We are now developing a measurement system for carefully determining the three dimensional strain effects in A-15 superconductors. The potential financial consequences of these measurements for very large accelerator magnets are considerable.

We will develop the measurement techniques and obtain the data base needed to generalize the Strain Scaling Law from one to three dimensions.

Accomplishments

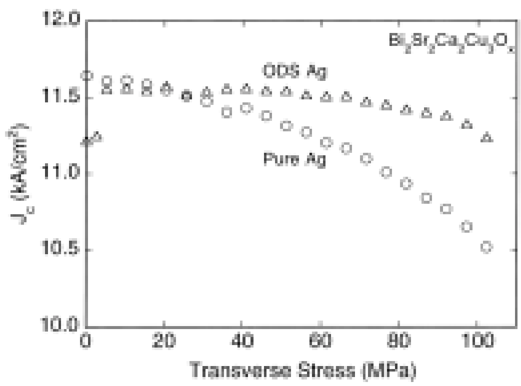
- Measurements of Transverse Stress on Coated High Temperature Superconductors — We made the first measurements of the transverse stress effect in second-generation high temperature superconductors, Y-Ba-Cu-O-coated rolling assisted biaxially textured substrates (RABiTS) and ion beam assisted deposition (IBAD) tapes. Before these measurements, the available electromechanical data on these conductors were limited to a few measurements of bending strain versus critical current.



Effect of transverse compressive stress on the critical current of Y-Ba-Cu-O-coated IBAD superconducting tape.

The electromechanical performance of the RABiTS conductor, which consists of brittle superconductor and buffer layers deposited on a soft, pure Ni substrate, was particularly suspect. However, the tests revealed that specimens of both the IBAD and the RABiTS conductors were able to tolerate stresses exceeding 100 megapascals with less than 7 percent degradation of critical current. These initial results suggest that these conductors will be suitable for high transverse stress applications, such as dipole magnets for high energy physics accelerators.

- Effect of Compressive Stress on Critical Current of $Bi_2Sr_2Ca_2Cu_3O_x$ Tapes — In collaboration with American Superconductor Corporation, we completed the first comparative study on the effect of transverse compressive stress on the critical current of $Bi_2Sr_2Ca_2Cu_3O_x$ multifilamentary tapes. Before these measurements, there had been considerable speculation that Bi-Sr-Ca-Cu-O/Ag tapes would be highly susceptible to critical current degradation from transverse stress. On the contrary, in this study we found that most specimens of $Bi_2Sr_2Ca_2Cu_3O_x$ tape with a pure Ag matrix exhibited less than 10 percent degradation at the maximum applied transverse stress of 100 megapascals. Furthermore, most specimens with a composite matrix of pure-Ag/oxide-dispersion-strengthened-Ag (ODS) exhibited negligible degradation at the same stress level. One ODS tape was tested at higher stress levels, approaching 150 megapascals, also with negligible degradation. This was a key result for applications of $Bi_2Sr_2Ca_2Cu_3O_x$ superconductors to superconductor motors, generators, and magnetic energy storage.



Comparative effects of transverse compressive stress on the critical current of $Bi_2Sr_2Ca_2Cu_3O_x$ tapes with pure-Ag and ODS-Ag matricies.

- Superconductor Interface Noise Measurements — As part of our superconductor interface research this past year, we conducted the first measurements of the noise characteristics of Y-Ba-Cu-O junction interfaces. We found that the normalized resistance noise per junction area is remarkably insensitive to temperature over a wide range, from 4 kelvins to 77 kelvins, and also independent of junction fabrication technique. These properties make it possible for superconducting electronic design engineers to apply our results, with proper scaling, to address critical engineering issues such as device operating frequencies and bandwidth. Indeed, the design equation has already played a key role in the design of contacts for high temperature superconducting detector coils in a new generation of commercial magnetic resonance imaging systems being developed by DuPont and Intermagnetics General Corporation.

Recent Publications

S. L. Bray, J. W. Ekin, C. C. Clickner, and L. Masur, "Transverse Compressive Stress Effects on the Critical Current of Bi-2223/Ag Tapes Reinforced with Pure Ag and Oxide-Dispersion-Strengthened Ag," J. Appl. Phys., submitted.

Y. Xu and J. W. Ekin, "Tunneling Characteristics and Low-Frequency Noise of High-T_C Superconductor/Noble-Metal Junctions," Proc. 17th Symp. Energy Eng. Sci., U.S. Dept. of Energy, CONF-990001, 17-25 (November 1999).

P. E. Kirkpatrick, J. W. Ekin, and S. L. Bray, "A Flexible High-Current Lead for Use in High-Magnetic-Field Cryogenic Environments," Rev. Sci. Instrum. **70**, 3338-3340 (August 1999).

Y. Xu, J. W. Ekin, and C. C. Clickner, "Low-Frequency Noise of YBCO/Au Junctions," IEEE Trans. Appl. Supercond. **9**, 3990-3993 (June 1999).

Y. Xu, J. W. Ekin, C. C. Clickner, and R. L. Fiske, "Oxygen Annealing of YBCO/Gold Thin-film Contacts," Adv. Cryo. Eng. (Materials) **44**, 381-387 (December 1998).

Josephson Array Development

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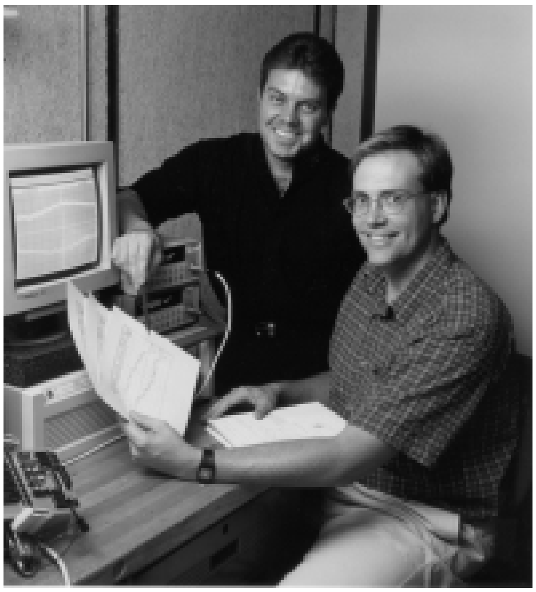
Project Goals

Develop superconducting electronic circuit and system technology for fundamental, quantum-based DC and AC voltage standard systems; to provide improved standards for fundamental metrology and support U.S. industry test and measurement applications.



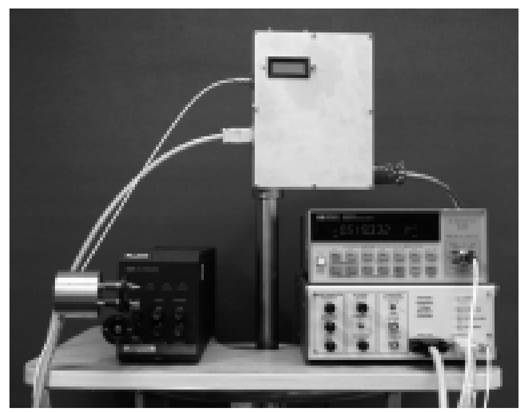
Charlie Burroughs and Sam Benz discuss the operating margins of a pulse driven Josephson junction array.

Customer Needs

The demands of modern technology for accurate voltage calibrations have gradually exceeded the capability of classical artifact standards. To meet current needs, an international agreement signed in 1990 redefined the practical volt in terms of the voltage generated by a superconductive integrated circuit developed at NIST and the Physikalisch-Technische Bundesanstalt in Germany. This circuit contains thousands of superconducting Josephson junctions, all connected in a series array and biased at a microwave frequency. The voltage developed by each junction depends only on fundamental constants and, thus, the circuit never needs to be calibrated. This allows any standards or commercial laboratory to generate highly accurate voltages without the need to transfer an artifact standard. This advance has improved the uniformity of voltage measurements around the world by about a hundred fold. These systems are rapidly becoming essential for meeting legal and accreditation requirements in commercial, governmental, and military activities.

The U.S. electronics instrumentation industry maintains its world position through the development and deployment of increasingly accurate, easier-to-use instruments. Providing U.S. industry with quantum voltage standard systems gives these customers, with appropriate oversight from the NIST Electricity Division, immediate realization of the highest possible in-house accuracy. These customers also benefit dramatically by removing their dependence on less accurate reference standards that require frequent calibration.

We also support the standards community by developing voltage standard systems with new capabilities, including lower cost, increased functionality, and ease of use. Other customers are the superconducting electronics community and the U.S. military, which we support through development of novel superconducting circuits, high performance systems, and technical expertise and consulting.

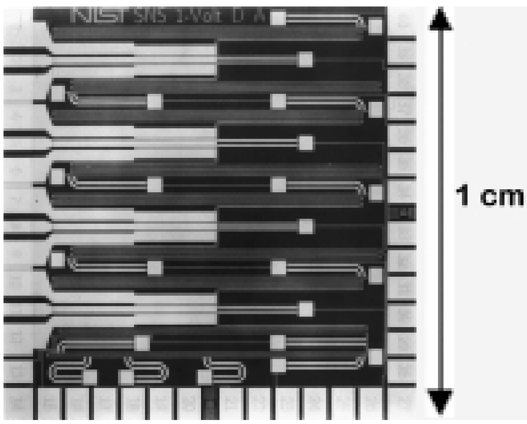


Traveling Josephson voltage standard system showing the bias electronics (right), microwave probe electronics (middle) and a Zener reference (left).

Technical Strategy

Over the past 20 years, this project has developed superconducting Josephson junction array technology for quantum voltage standard systems. NIST groundbreaking work led to commercialization of the first DC Josephson voltage standard. Recent improvements in system design and operation have led to a traveling Josephson voltage standard system that is compact, low cost, and transportable for calibration of Zener reference standards. This technology has recently been transferred directly to the private sector.

Over the past few years, we have developed a novel superconductor-normal-superconductor (SNS) junction technology that adds the features of stability and programmability to the accuracy of conventional Josephson voltage standards. This new programmable Josephson voltage standard system is being used in a number of metrology experiments, namely the watt experiments at NIST and Switzerland's Federal Office of Metrology (OFMET) and the metrology triangle experiment at NIST and France's Central Laboratory for Electrical Industry (LCIE), where these features should reduce the uncertainty of the experimental measurements.



A 1 centimeter _ 1 centimeter superconducting integrated circuit with 32 768 SNS Josephson junctions for the 1 volt programmable voltage standard.

The NIST Electricity Division is interested in improving the internal efficiency of its maintenance and dissemination of the volt through the development and deployment of an improved one volt programmable voltage standard. We will work with Electricity Division staff to develop a Josephson voltage standard that can be used more directly in the customer calibration system.

We provide systems and support to NIST and other national metrology laboratories for Josephson voltage standard systems.

Our present primary goal is to develop the world's first quantum mechanically accurate voltage source for AC and DC metrology. The device is effectively a digital-to-analog converter capable of synthesizing arbitrary waveforms using the perfectly quantized pulses of Josephson junctions. The concept for this new device was co-invented by NIST and Northrop-Grumman researchers in 1996. Present AC voltage standards are based on AC-DC thermal voltage converters. A quantum-based AC source would provide an entirely new instrument and methodology for AC metrology. The major challenge of this technology is to achieve practical output voltages by developing novel submicrometer junctions and improved broadband circuits.

We will develop an AC voltage source with an output voltage of 1 volt.

NIST's 1 volt programmable voltage standard system showing (left to right) low thermal probe, microwave and high speed bias electronics, and computer control.

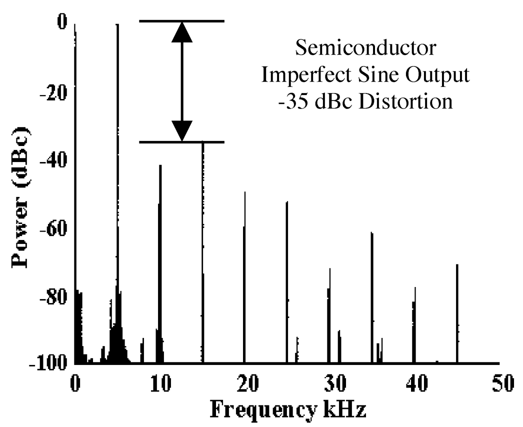
The concept of an arbitrary voltage waveform generator with quantum mechanical accuracy has enabled the possibility of making an electronically based thermometer. The quantum-based waveform generator can be used to synthesize an equivalent noise voltage with a known, calculable noise spectrum. This quantized noise source can be used to calibrate the correlator measurement electronics of a Johnson noise thermometry system. In collaboration with the Chemical Science and Technology Laboratory's Process Measurements Division, we have been awarded a competence grant to develop this new quantum-based electrical thermometer.

We will develop a quantized voltage noise source for calibration of a Johnson noise thermometer.

Accomplishments

- New Traveling System Completed — The U.S. Department of Energy (DOE) has adopted a traveling Josephson voltage standard for use in DOE metrology centers. The new standard was developed in collaboration among NIST, Sandia National Laboratory (SNL), and the National Aeronautics and Space Administration. Our role was the design of the hardware and software, and the construction and initial testing of the system. The new standard is a compact, integrated system with fully automatic operation, self-testing, and complete documentation. Its primary use is the calibration of Zener reference standards, where it achieves the same accuracy as NIST's primary voltage standard. During the next year, DOE plans to rotate the new standard through eight metrology centers, where it will provide direct traceability to the Josephson representation of the SI volt. After about six weeks at each center, it will be shipped in a single 40 kilogram container to the next user. Eighteen DOE metrology personnel recently gathered at SNL for a three day, hands-on training course in the operation of the new system.

■ First Programmable System Delivered — The first 1 volt programmable Josephson voltage standard system has been completed and delivered to the Electricity Division's watt experiment. The system operates as an instrument that can be controlled to produce any voltage within its output range of ±1.1 volt. When not being used as a voltage reference, the system automatically executes a variety of self tests to confirm correct operation and to evaluate uncertainties. Once set up, the system can operate unattended 24 hours a day. It will be directly connected as the voltage reference for the watt experiment and is expected to eliminate uncertainties associated with a chain of voltage comparisons used previously.



Digitally synthesized 5 kilohertz sine wave from a semiconductor showing harmonic distortion at 35 decibels below the fundamental frequency. High harmonic distortion indicates an imperfectly synthesized waveform.

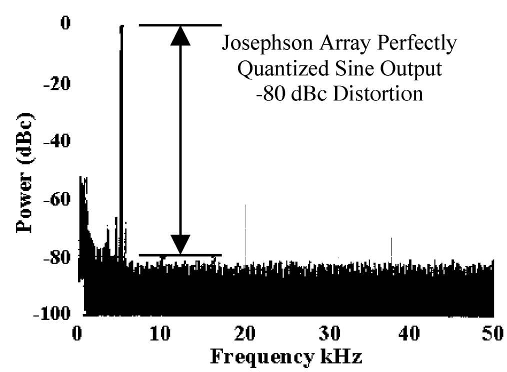
■ Higher Output Voltage Demonstrated — After co-inventing the pulse-programmable AC voltage standard, we theoretically and experimentally demonstrated that synthesizing AC waveforms with perfectly quantized pulses recreates the harmonic spectrum of an ideal digital code. The main challenge for the waveform generator is achieving practical output voltages. We have applied for a patent on a method to create a bipolar output voltage with a six-fold increase in output power, by driving the Josephson array with a combined input of both a digital code and a microwave signal. Bipolar sine waves have been generated with harmonic distortion reduced to 80 decibels below the fundamental, a 45 decibel improvement over the semiconductor digital code spectrum. A bipolar square wave with 150 millivolt amplitude has been demonstrated using 4096 SNS junctions.

Collaborations

■ Charlie Burroughs is collaborating with Blaise Jeanneret of OFMET, Switzerland to implement a programmable voltage standard for OFMET's Watt experiment. An advanced probe and programmable 1 volt chip have been delivered.

■ Charlie Burroughs collaborated with Hitoshi Sasaki from Japan's Electrotechnical Laboratory (ETL) to perform a highly accurate comparison between the Josephson based fast reversed DC (FRDC) source and a conventional semiconductor FRDC source. The measured uncertainty at 1 volt was 1 part in 10^7.

■ Charlie Burroughs has completed and delivered the bias electronics to Gerard Geneves of LCIE, France. They now have a complete NIST-developed programmable voltage standard system which they will use as one corner of a quantum-based metrology triangle experiment comparing resistance, current and voltage.



Synthesized 5 kilohertz sine wave from a 1000 junction array. The undesired harmonics are reduced to 80 decibels below the fundamental frequency because of perfect quantization by the superconducting Josephson junctions.

■ Sam Benz is collaborating with Wilfred Booij at the University of Cambridge on submicrometer junction fabrication development for lumped arrays. Superconducting integrated circuits have been exchanged for fabrication and testing. Constant voltage steps were demonstrated in arrays of 10 bilayer Nb-PdAu SNS junctions defined by focused ion beam.

■ Sam Benz is collaborating with researchers at Japan's ETL to develop cryocooler compatible Josephson junctions for programmable voltage standards. Using NIST designed circuits and masks, ETL has fabricated and delivered two wafers using their high temperature NbN-TiN-NbN junction process.

- Sam Benz is collaborating with Northrop Grumman on the development of a pulse-quantized AC waveform generator for radar applications. The application uses the same pulse-quantized AC synthesis techniques as the metrology application except at radar frequencies. We have designed and fabricated SNS junction circuits using Northrop Grumman designs.

Recent Publications

C. A. Hamilton and Y. H. Yang, "Evaluating the Uncertainty of Josephson Voltage Standards," Metrologia **36**, 53-58 (March 1999).

S. P. Benz, C. J. Burroughs, T. E. Harvey, and C. A. Hamilton, "Operating Conditions for a Pulse-Quantized AC and DC Bipolar Voltage Source," IEEE Trans. Appl. Supercond. **9**, pp.3306-3309 (June 1999).

A. H. Miklich (Northrup Grumman), J. X. Przybysz, T. J. Smith, S. P. Benz, and T. E. Harvey, "Superconducting Thin-Film Transformers at Microwave Frequencies," IEEE Trans. Appl. Supercond. **9**, 3062-3065 (June 1999).

C. J. Burroughs, S. P. Benz, T. E. Harvey, and C. A. Hamilton, "1 Volt DC Programmable Josephson Voltage Standard," IEEE Trans. Appl. Supercond. **9**, 4145-4148 (June 1999).

S. P. Benz, C. A. Hamilton, C. J. Burroughs, and T. E. Harvey, "AC and DC Bipolar Voltage Source Using Quantized Pulses," IEEE Trans. Instrum. Meas. **48**, 266-269 (April 1999).

C. J. Burroughs, S. P. Benz, C. A. Hamilton, T. E. Harvey, J. R. Kinard, T. E. Lipe, and H. Sasaki, "Thermoelectric Transfer Difference of Thermal Converters Measured with a Josephson Source," IEEE Trans. Instrum. Meas. **48**, 282-284 (April 1999).

C. J. Burroughs, S. P. Benz, C. A. Hamilton and T. E. Harvey, "Programmable 1 Volt DC Voltage Standard," IEEE Trans. on Instrum. Meas. **48**, 279-281, (April 1999).

Nanoscale Cryoelectronics

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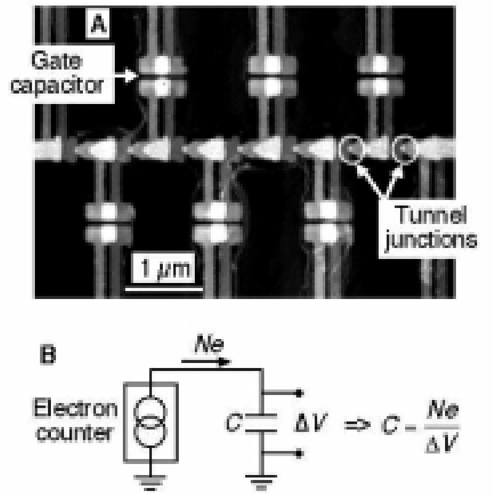
Project Goals

Develop novel integrated circuits for metrology based on the unique properties of electronic devices operating at temperatures below one kelvin.



Atomic force microscope image of an electron counter, the heart of a new capacitance standard based on counting electrons. The standard, shown in the schematic, consists of the electron counter, a capacitor, and a single electron electrometer to monitor the process (not shown). The electron counter, based on seven nanometer-scale tunnel junctions in series, can "pump" electrons onto the capacitor with a error rate less than 1 electron in 10^8.

Customer Needs

We work in two principal areas: single electron devices and microcalorimeter-based detectors. The goal of the single electron project is to use the unique capabilities of single electron tunneling (SET) devices to create new quantum standards based on the manipulation of single electrons and to develop measurement techniques applicable to new generations of electronics that will operate with very few electrons. The goal of the microcalorimeter detector project is to use the unique low noise, high sensitivity properties of cryogenic electronics to create new generations of detectors for high energy resolution measurements of radiation, from infrared through X-ray, and for mass spectrometry of large molecules.

Single Electron Devices for Electrical and Photonic Standards

The U.S. electronics industry continues to seek improved and more accessible standards for maintaining instrument calibration. NIST is working to support this need through the development of intrinsic standards based on fundamental physical principles, such as the volt, based on the Josephson effect, and the ohm, based on the quantum Hall effect. For capacitance, NIST's primary standard (the calculable capacitor) is a unique instrument that is difficult to replicate, and it provides the best accuracy at only one fixed frequency.

We are focused on producing a capacitance standard based on counting electrons. This standard will provide accurate calibrations over a wide range of frequencies and will be more easily replicated to meet customers' needs. This same technology is being explored as a way to create new optical calibration devices based on the production of single photons.

Cryogenic Detectors

The ability to detect photons with high energy resolution and near unity quantum efficiency will enable new generations of spectroscopic tools to be created. Improved energy dispersive X-ray spectroscopy will be used to solve a wide range of materials analysis problems. For example, the semiconductor manufacturing industry needs improved X-ray materials analysis to identify small contaminant particles on wafers.

To make this technology available to the materials analysis community, NIST has licensed several patents to two U.S. companies for commercialization. Additionally, NIST's Chemical Science and Technology Laboratory will use this spectroscopy to improve its own materials analysis capability. The National Aeronautics and Space Administration (NASA) is also in need of improved instruments for imaging at wavelengths from infrared to X-ray. We are working with NASA to bring this technology into use.

The same devices can be used, in principle, to greatly enhance mass spectrometry of high mass biomolecules, such as DNA, which will be of great importance to the biotechnology community.

Technical Strategy

Single Electron Devices for Electrical and Photonic Standards

The creation of electronic devices capable of manipulating and detecting individual electrons has opened the door to the development of entirely new standards and metrology tools. SET devices are made possible by a combination of state-of-the-art nanolithography to create the nanometer-scale devices, millikelvin cryogenics to cool the devices to their operating temperature, custom low noise electronics to operate and measure the devices, and fundamental physics, to understand and diagnose the operation of the devices. Maintaining expertise and capabilities across these fields represents the core technical strategy of this effort.

We will develop a theoretical model for the effect of high frequency noise on SET devices and test specific predictions for the performance of electron pumps in the presence of such noise.

At present, the main application for SET devices within the project is to create a new capacitance standard based on the fundamental definition of capacitance: capacitance equals charge divided by voltage, $C=Q/V$. By placing a known number of electrons on a capacitor, and measuring the voltage across the capacitor, C can be determined. A prototype of such a standard has been demonstrated with a repeatability of order 1 part in 10^7. In order to confirm the accuracy of the standard, a portable version must be taken to NIST in Gaithersburg for a direct comparison with the calculable capacitor.

In collaboration with Electricity Division, we will build a new copy of the capacitance standard in a transportable dilution refrigerator. We will confirm its operation and take it to Gaithersburg for comparison against the calculable capacitor.

SET devices can also be used as tools to measure the performance of other devices that operate with individual electrons. Under a new NIST-funded "Competence" program, work will begin on creating a new class of electronic devices designed to produce single photons on demand. These devices will be based on quantum dots of semiconductor materials. To understand their behavior, it will be necessary to measure the electrical currents into the dots at the single electron level. This can be done only using SET technology.

In collaboration with the Optoelectronics and Semiconductor Electronics Divisions, we will integrate SET devices into a single photon circuit and confirm the electrical operation of the photon source.

Cryogenic Detectors

Introducing a radically new technology such as cryogenic microcalorimeters to a large community requires creating and demonstrating an entire measurement instrument, and not just the detector. In this case, we have developed superconducting electronics to read the detectors, compact adiabatic demagnetization refrigerators to simplify cooling the detectors to millikelvin operating temperatures, and room temperature electronics to process the output signals. The resulting system makes a much more compelling case for the technology than the performance specifications of the detector alone. Thus, our goal is to develop new detector systems and to apply the systems to problems of interest to our customers.

In the area of X-ray spectroscopy, the performance target depends on the application. For materials analysis, further improvements in energy resolution are not as important as an increase in the maximum count rate and collection area. This can be achieved by the creation of multipixel arrays of detectors. In addition to the fabrication difficulties in making such arrays, the cold and room temperature electronics to read the arrays must also be created. The current approach to the electronics is to develop a superconducting quantum interference device (SQUID) multiplexer (MUX) circuit to read the array, and room temperature digital signal processing (DSP) to process the MUX signals.

We will develop a small array of microcalorimeter detectors for X-ray analysis and read them using SQUID MUX and DSP circuitry.

The application of X-ray detectors to materials analysis problems represents a test bed for this technology. With a focus towards the semiconductor manufacturing industry, problems in characterization of small particles and very thin layers of material are very important. The ability of the detector to differentiate overlapping X-ray lines at low energies enables analysis of previously inaccessible systems.

We will demonstrate a capability to perform spatial mapping of the chemical bonding state of various elements, differentiating Al from Al_2O_3, for example.

For astronomical observations, improvements in the energy resolution at relatively high X-ray energies (6 thousand electron volts) are still needed. In addition, large format, densely packed arrays of detectors are required for imaging. These are ambitious goals that will require improved understanding of the limitations on performance of microcalorimeter detectors. Novel fabrication techniques will need to be developed to make densely packed arrays, and

SQUID MUX and DSP circuitry will be required to read the arrays.

We will develop models of single pixel microcalorimeter performance to assist in improving detector sensitivity.

We will develop small, densely packed arrays of detectors and instrument them with appropriate read electronics.

These detectors also provide remarkable performance at lower energies, from infrared through visible. Here the goal is clearly to develop large format imaging arrays with high sensitivity and energy resolution. The present application for these arrays is in astronomy, both ground based and in space.

In collaboration with the High Performance Sensors, Infrared Detectors and Mixers Project, we will develop an array of microcalorimeter detectors optimized for infrared astronomy along with the necessary SQUID MUX and room temperature DSP electronics to read the array.

Since these microcalorimeter detectors work by measuring the energy deposited on the detector from any source, they can be used to measure the kinetic energy associated with the impact of a molecule in a mass spectrometer. In principle, they should work with high efficiency even for molecules of very high mass, where conventional detectors are no longer useful. This could greatly enhance mass spectrometry of very high mass molecules like DNA, provided a means for launching such molecules can be found.

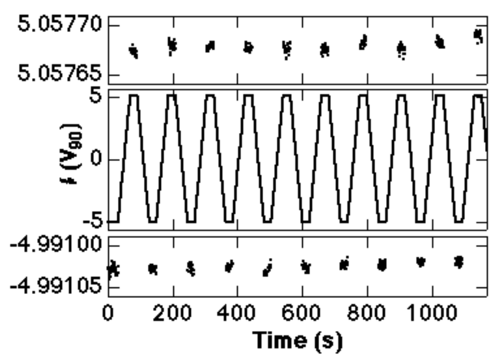
We will demonstrate a method for launching molecules of large mass into a magnetic sector mass spectrometer, and use this instrument to compare the efficiency of conventional and microcalorimeter detectors.

Accomplishments

Single Electron Devices for Electrical and Photonic Standards

- The past two years have brought to fruition the results of a decade of research into single electron tunneling (SET) electronics. The goal of this work has been to develop a capacitance standard based on counting electrons. A thorough understanding of the physics of SET devices has been necessary to perform electron counting with metrological accuracy. The fundamental error mechanisms in the electron pump have been the subject of theoretical and experimental investigations in the project for several years. The development of an experimental technique for characterizing individual junctions in the pump made possible the first quantitative comparison between experiment and theory in the regime of very rare errors. This comparison showed that the pump was not performing nearly as well as the standard theory predicted. Experiments and theoretical work on the effect of photon-assisted tunneling, which is not included in the standard theory, have shown that this is the origin of the discrepancy. The likely source of the photons is fluctuating background charges in the substrate or in the pump itself.

- A prototype of a capacitance standard based on counting electrons has now been demonstrated. The components of the standard are an electron counter, a capacitor, and an electrometer to monitor the process. The electron counter is based on seven, nanometer-scale tunnel junctions in series. It can "pump" electrons onto the capacitor with an error rate less than 1 electron in 10^8. The electron pumping is monitored with an SET based electrometer fabricated on the same chip as the pump, with a charge sensitivity better than 10^{-2} electrons. The capacitor, fabricated by Neil Zimmerman in the Electricity Division, operates at cryogenic temperatures and uses vacuum as the dielectric, resulting in a frequency-independent capacitance.

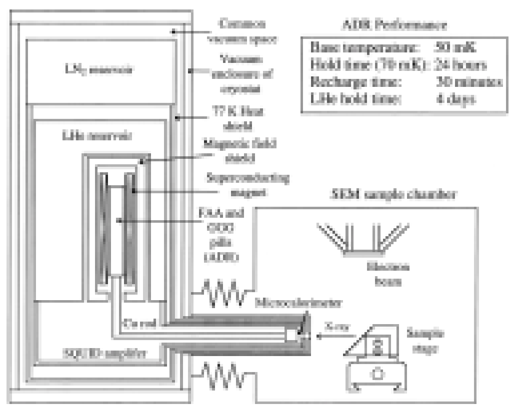


Demonstration of pumping electrons on an off a prototype capacitance standard.

To operate the standard, approximately 100 million electrons are placed, one at a time, on the capacitor. The voltage across the capacitor is then measured, resulting in a "calibration" of the cryogenic capacitor. This capacitance can then be transferred to room temperature using a standard AC bridge measurement technique. The figure below shows the result of pumping electrons on and off the capacitor, with a 20 second pause when fully charged to measure the voltage (shown in expanded view above and below). The result is a value of capacitance with a repeatability of 1 part in 10^7.

Cryogenic Detectors

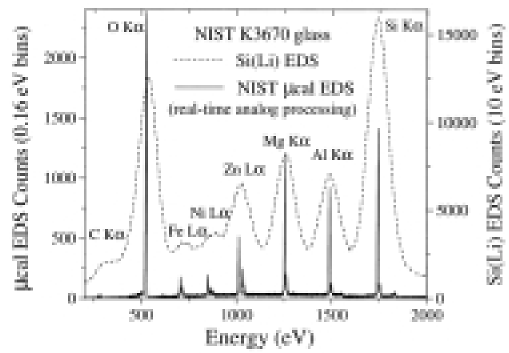
■ The success of the microcalorimeter detector project has been made possible by the broad expertise within the Division in such fields as physics of superconductivity, device fabrication including Si micromachining, superconducting electronics, cryogenic engineering, and low noise, room temperature electronics. Without expertise in all these areas, the complete systems that have provided the compelling demonstrations for the power of this technology would not have been possible. As an example, the schematic below shows a microcalorimetric energy dispersive spectrometer (EDS) X-ray detector system inserted into a scanning electron microscope to allow chemical microanalysis of materials.



Schematic of a microcalorimetric energy dispersive spectrometer (EDS) X-ray detector system inserted into a scanning electron microscope.

■ The microcalorimetric detector uses a superconducting/normal-metal bilayer to create a superconducting transition-edge sensor (TES). Using the proximity effect, the transition temperature of the bilayer can be selected to match each specific application. We created an accurate model of the proximity effect in this system which allows the thickness for each layer to be calculated, minimizing trial-and-error fabrication.

■ Originally each TES was individually fabricated using Al/Ag bilayers and a shadow mask deposition process, but recent advances with Mo/Cu bilayers has allowed whole wafer photolithographic processing, dramatically improving yield. The TES and appropriate X-ray absorber are fabricated on a Si_3N_4 micromachined membrane to produce the required thermal isolation. The device operates using a current bias and extreme negative electrothermal feedback, so that it self-regulates in temperature. Absorbed X-rays produce heat pulses in the device which are read as pulses of reduced bias current by a first stage, single SQUID amplifier located adjacent to the detector to minimize inductance. The output of the first stage SQUID is read by a unique 100-SQUID amplifier invented and fabricated here specifically to allow direct coupling of the signal to room temperature electronics. The detector is cooled to below 100 millikelvins by a compact adiabatic demagnetization refrigerator that has unique design features that produce nearly 24 hours of continuous operation, and days of liquid He hold time.



Comparison of resolutions of NIST micro-calorimeter EDS to standard semiconductor energy dispersive detector.

This system holds the world record for energy resolution for an EDS detector of 2.0 electron volts at 1500 electron volts, which is over 30 times better than the best high resolution semiconductor-based detectors currently available. The figure below compares an X-ray spectrum obtained with this system to that from a semiconductor energy dispersive detector, clearly demonstrating the remarkable improvement in resolution. The specimen was a glass prepared by Dale Newbury of the Chemical Science and Technology Laboratory to use as a test standard for EDS. We have used the system to identify submicrometer particles of materials such as W on Si substrates, an identification problem that is impossible with standard EDS detectors and of great importance to the semiconductor industry. It has also demonstrated, for the first time, energy shifts in the EDS X-ray spectra of materials such as Al, Fe, and Ti, depending on their chemical bonding state, thus allowing differentiation between a particle of Al and Al_2O_3, for example.

Based on these types of results, two U.S. X-ray spectrometer companies sought licenses for a suite of patents covering this technology to begin commercialization. Technology transfer to both companies is currently underway.

- In addition to X-ray detection, this microcalorimeter technology is being developed for use at other wavelengths, to measure power rather than energy. In collaboration with the High Performance Sensors, Infrared Detectors and Mixers Project, our TES bolometers have achieved world record sensitivity. This impressive result confirms the utility of this technology for this application as well. However, to meet the needs of NASA, large format arrays of these detectors have to be fabricated and electronics have to be created to read the arrays. The collaboration has developed the first SQUID-based multiplexer circuit (MUX) for this purpose, and has demonstrated it with a 1 _ 8 array of TES bolometers. The ability to create multiplexed readouts may, in the end, prove even more important that the performance of the detectors themselves. The huge amount of data from this system will require new room temperature electronics to collect and process the information. We developed a first generation digital signal processing system and have successfully interfaced it with the SQUID amplifiers, providing the feedback required for their operation.

- This detector technology is also being explored as a means of dramatically improving the quantum efficiency of mass spectrometers for high mass molecules. The microcalorimeter can detect the kinetic energy associated with the impact of a molecule on the detector. In principle, this should work to extremely high masses, where current detectors have very low efficiency. The detector was tested on a simple time-of-flight mass spectrometer; it successfully identified a number of large biomolecules. The detector is currently installed on a high resolution magnetic sector mass spectrometer, where direct comparison with conventional detectors will be possible.

Recognition

- Department of Commerce Gold Medal, 1998
- NIST Applied Research Award, 1998

Patents

- "Mechanical Support for a Two Pill Adiabatic Demagnetization Refrigerator," issued August 1999.
- "Superconducting Transition-Edge Sensor," issued March 1999.
- "Microcalorimeter X-ray Detectors with X-ray Lens," issued March 1999.
- "Superconducting Transition-Edge Sensor with Weak Links," filed November 1998.

Recent Publications

A. L. Eichenberger, M. W. Keller, J. M. Martinis, and N. M. Zimmerman, "Frequency Dependence of a Cryogenic Capacitor Measured Using Single Electron Tunneling Devices," submitted.

M. Covington, M. W. Keller, R. L. Kautz, and J. M. Martinis, "Photon-Assisted Tunneling in Electron Pumps," submitted.

J. A. Chervenak, K. D. Irwin, E. N. Grossman, J. M. Martinis, C. D. Reintsema, C. A. Allen, D. Bergman, S. H. Moseley, and R. Shafer, "Performance of Multiplexed SQUID Readout for Cryogenic Sensor Arrays," Nuclear Inst. Methods A, in press.

K. D. Irwin, G. C. Hilton, J. M. Martinis, S. Deiker, N. F. Bergren, S. W. Nam, D. A. Rudman, and D. A. Wollman, "A Mo-Cu Superconducting Transition-Edge Microcalorimeter with 4.5 eV Energy Resolution at 6 keV," Nuclear Inst. Methods A, in press.

J. M. Martinis, G. C. Hilton, K. D. Irwin, and D. A. Wollman, "Calculation of T_C in Normal-Superconductor Bilayer Using the Microscopic-Based Usadel Theory," Nuclear Inst. Methods A, in press.

D. A. Wollman, S. W. Nam, D. E Newbury, G. C. Hilton, K. D. Irwin, N. F. Bergren, S. Deiker, D. A. Rudman, and J. M. Martinis, "Superconducting Transition-edge-Microcalorimeter X-ray Spectrometer with 2eV Energy Resolution at 1.5 keV," Nuclear Inst. Methods A, in press.

D. A. Wollman, D. E. Newbury, G. C. Hilton, K. D. Irwin, L. L. Dulcie, and J. M. Martinis, "Microcalorimeter EDS Measurement of Chemical Shifts in Fe Compounds," Microscopy and Microanalysis, in press.

D. A. Wollman, K. D. Irwin, G. C. Hilton, L. L. Dulcie, N. F. Bergren, D. E. Newbury, and J. M. Martinis, "Microcalorimeter EDS with 3 eV Energy Resolution", Proc. 14th Int. Cong. Electron Micro., in press.

M. W. Keller, A. L. Eichenberger, J. M. Martinis, and N. M. Zimmerman, "A Capacitance Standard Based on Counting Electrons," Science, **285**, 1706-1709 (September 1999).

R. L. Kautz., M. W. Keller, and J. M. Martinis, "Leakage and Counting Errors in a Seven-Junction Electron Pump," Phys. Rev. B **60**, 8199-8212 (September 1999).

C. K. Stahle, D. McCammon, K. D. Irwin, "Quantum Calorimetry," Physics Today **52**, 32-37 (August 1999).

J. A. Chervenak, K. D. Irwin, E. N. Grossman, J. M. Martinis, C. D. Reintsema, M. E. Huber, "Superconducting Multiplexer for Arrays of Transition Edge Sensors," Appl. Phys. Lett. **74**, 4043-4045 (June 1999).

G. C. Hilton, D. A. Wollman, K. D. Irwin, L. Dulcie, N. F. Bergren, and J. M. Martinis, "Superconducting Transition-Edge Microcalorimeters for X-ray Microanalysis," IEEE Trans. Appl. Supercond. **9**, 3177-3181 (June 1999).

D. E. Newbury, D. A. Wollman, K. D. Irwin, G. C. Hilton, and J. M. Martinis, "Lowering the Limit of Detection in High Spatial Resolution Electron Beam Microanalysis with the

Microcalorimeter Energy Dispersive X-Ray Spectrometer," Ultramicroscopy **78**, 73-88 (February 1999).

D. A. Wollman, G. C. Hilton, K. D. Irwin, N. F. Bergren, D. A. Rudman, D. E. Newbury, and J. M. Martinis, "Cryogenic Microcalorimeters for X-ray Microanalysis," Proc. 1999 Nat. Conf. Stand. Lab. (NCSL) Workshop and Symp., 811-819 (July 1999).

High Performance Sensors, Infrared Detectors, and Mixers

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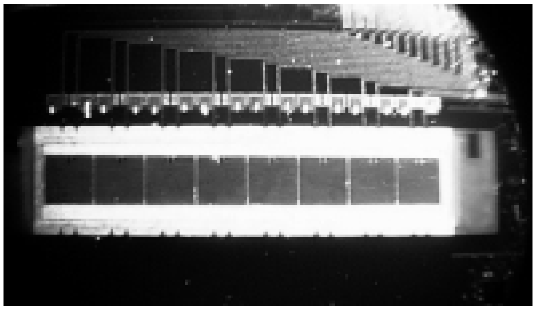
Project Goals

Develop and apply cryogenic electronic technology to measurements and standards in support of other NIST and U.S. industry.



A 1 _ 8 array of 300 millikelvin bolometers.

Customer Needs

The U.S. aerospace and defense industries are being pushed toward both higher performance and faster, less expensive systems. Devices originally developed for cryogenic electronics, in particular cryogenic bolometers and tunnel diodes, are often useful in a wide variety of metrological applications, as well as in other scientific or commercial applications, not always at cryogenic temperatures. These applications focus chiefly on the detection or manipulation of light from millimeter to infrared wavelengths. The activities of this project focus on adapting such devices for the benefit of these industries, either directly through collaborative research and development programs, or indirectly, through improving the metrological capabilities of other NIST Divisions, which in turn make the results available to U.S. industry.

Technical Strategy

The work of this project focuses particularly on two types of devices, bolometers and tunnel junctions, initially developed for cryogenic electronic applications, but also useful in the detection or frequency conversion of radiation from millimeter to infrared wavelengths. Work on improving the sensitivity or precision of power measurements exploits the low noise properties of thin film bolometers. Work on improving the frequency coverage and efficiency of frequency conversion (i.e., rectification and mixing) exploits the low capacitance and nonlinear transport properties of tunnel diodes.

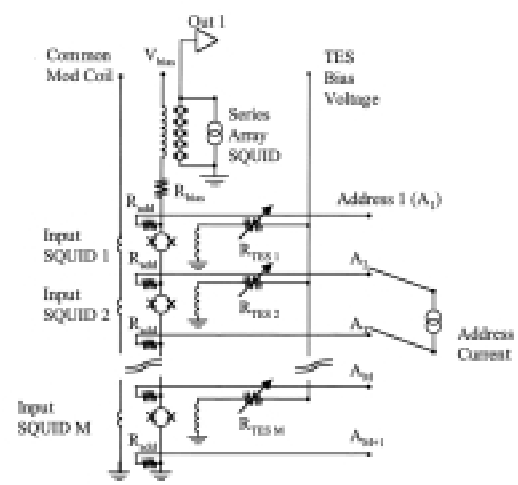
One focus is the development of bolometers with ever higher sensitivity, with low noise-equivalent power (NEP) for far-infrared (IR) wavelengths. The chief customer in this case is the National Aeronautics and Space Administration (NASA) and its contractors, the application being space based astronomy.

We will develop a high sensitivity bolometer for far-IR wavelengths with an NEP of less than 10^{-18} watts per root hertz.

A related focus is the development of large arrays of moderately low NEP bolometers. These are applicable for remote sensing of the Earth, atmospheric spectroscopy, and astronomy.

We will develop a 32 _ 32 element bolometer array with NEP less than 5 _ 10^{-17} watts per root hertz.

Because readout is a critical element in any array technology, a SQUID-based cryogenic multiplexer is being developed to provide the front-end processing of the bolometer outputs. (These NASA-funded programs are collaborative with the Nanoscale Cryoelectronics project). In both cases, the bolometers are superconducting films biased on their transition-edge, and operated in an electrical substitution mode.



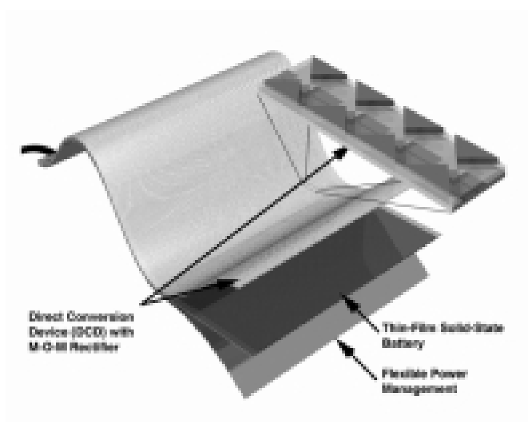
Monolithic SQUID multiplexer circuit. A 1 _ 8 prototype has been demonstrated at pixel rates of 1 megahertz.

Another focus is the application of such bolometers to standards-related metrology, both for audio frequencies (where they are known as AC-DC thermal transfer standards) and for IR frequencies (where they are known as electrical substitution radiometers). This project is collaborative with the Electricity Division, which is responsible for AC electrical calibration and metrology.

For audio frequencies, we will achieve precision better than 1 part in 10^6 in AC voltage transfer at microwatt power levels.

Another focus is on the application of tunnel junctions, originally developed for cryogenic electronics, to IR rectification and mixing applications. For decades, scientists have envisioned highly efficient generation of solar power by the direct rectification of sunlight in ultra-low capacitance diodes. Recent advances in nanoscale fabrication make such visions much more realistic; commercial firms and government agencies are now working with NIST to realize them using the nonlinearity of tunneling in uncooled, metal-insulator-metal (MIM) thin film diodes.

Our goal is to observe photon-assisted tunneling steps in uncooled MIM diodes at 30 terahertz. By 2001, we aim for operation at above 100 terahertz with AC to DC conversion efficiency greater than 20 percent.

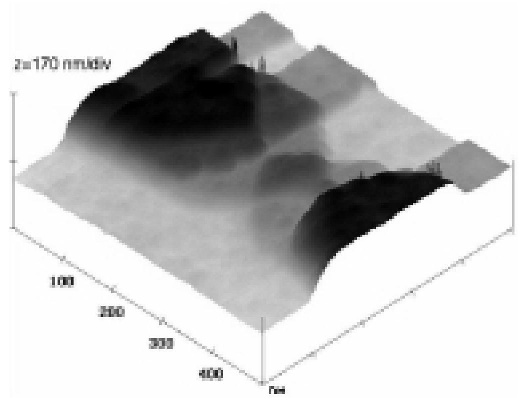


Direct solar energy conversion concept showing array of antenna coupled metal-insulator-metal diode rectifiers on flexible panel.

Separately, IR frequency synthesis and metrology have traditionally been done by harmonic mixing of the output of low frequency standards in whisker contacted tunnel diodes, and the same thin film MIM diodes we are developing will enable the creation of frequency synthesis systems that are much more compact, reliable, and user friendly.

Another focus is the development of thin film bolometers, coupled to antennas and operated at room temperature, in applications where the very highest sensitivity is not required. An example is millimeter-wave imaging for the detection of concealed weapons (clothing is transparent at millimeter wavelengths). In collaboration with the Electricity Division and the Office of Law Enforcement Standards, we are developing an actively illuminated imaging system for this application, based on a full wafer-scale array of several hundred antenna coupled bolometers.

We will develop am imaging system with reflectivity contrast less than 0.5 percent at 5 meters range in a 16 _ 16 element array.



Nanoscale metal-insulator-metal diode, 40 nanometers _ 40 nanometers, integrated with a dipole antenna.

In most of these programs, the lithographic antenna forms an important component of the system, frequently requiring as much development as the bolometer or tunnel diode, although its only function is the efficient coupling of radiation to the device. We therefore perform significant development work on lithographic antennas themselves. Moreover, the polarization-specific nature of antennas can frequently be exploited to provide our devices with additional functionality. For example, the emittance/reflectance properties of a surface differ for *s* and *p* polarizations of obliquely incident radiation. This can be exploited to resolve the ambiguity inherent in noncontact thermometry or materials analysis due to unknown specimen emissivity. In collaboration with a commercial semiconductor metrology manufacturer, we are exploring the potential of this technique.

Accomplishments

- First Electrical Substitution Radiometer Based on Superconducting Sensors — In 1997, we completed a standards-grade, electrical substitution radiometer for measurement of mid- and far-IR wavelength blackbody radiation, and delivered it to Div. 844, which is responsible for optical and IR power calibration and metrology. For an extended series of experiments covering a range of substitution power from 500 picowatts to 5 microwatts, the instrument's noise floor could be approximated as 4 picowatts plus 7 _ 10^{-6} times the measured power. We are now assisting a U.S. manufacturer of cryogenic radiometers with the incorporation of superconducting sensors into its products.

- First AC-DC Thermal Transfer Standard Based on Superconducting Sensors — In 1998, we completed and reported a set of preliminary experiments on AC-DC transfer using similar transition-edge bolometers. These yielded errors varying from 50 to 150 _ 10^{-6} (for frequencies from 100 hertz to 10 kilohertz), limited chiefly by inaccuracy introduced in delivering the AC signal to the cryogenic reference plane.

- First SQUID-Based Multiplexer for Transition-Edge Bolometers — In far-IR astronomy applications (both imaging and low-resolution spectroscopy), speed, and therefore sensitivity, are limited by the number of pixels that can be read simultaneously. Present far-IR bolometer arrays are already at the practical limit for low temperature wire count, so further improvement requires cold multiplexing. Over the last 2 years, a novel SQUID-based multiplexing scheme was conceived and demonstrated in a 1 _ 8 channel prototype. It operates at pixel rates up to 1 megahertz, and has sufficiently low noise to multiplex up to about 250 channels without degrading the system noise.

- First Monolithic Arrays of Transition-Edge Bolometers for Space Astronomy — These 1 _ 8 arrays are prototypes of a new generation of detector arrays for low background, far-infrared astronomy, and were spotlighted in a recent article in *Superconductor and Cryoelectronics* magazine. The Al-Ag or Mo-Au arrays are fabricated on micromachined Si structures that enable construction of closely packed two dimensional arrays by folding the "legs" back out of the focal plane. The bolometers operate with a 300 millikelvins base temperature, requiring ^{3}He refrigeration, and have a saturation power of about 5 picowatts and a time constant of about 2 milliseconds. Electrical NEP is phonon-noise limited at roughly 2 _ 10^{-17} watts per root hertz, the best ever reported for an IR bolometer operating with ^{3}He refrigeration, and within a factor of six of the best reported for any other IR bolometer.

- Uncooled Antenna-Coupled MIM Junctions for IR Rectification and Mixing — The ultra-low capacitance, fully lithographic diodes have areas as low as 30 _ 30 square nanometers and are fabricated by angled evaporation through a free-standing PMMA resist bridge defined by electron beam lithography. The diodes are coupled to planar dipole antennas designed for resonance at 10 micrometers wavelength. We have successfully fabricated and tested diodes from Al-AlO_x-Al, Al-AlO_x-Pd, and Nb-NbO_x-Ag materials. The nonlinear current-voltage characteristics are accurately predicted by the Brinkman-Dynes-Rowell theory of tunneling through trapezoidal barriers, both for the nano-MIMs and for separate, micrometer-sized Nb-NbO_x-Ag MIM diodes. The optical response of the nano-MIM diodes to 10 micrometers CO_2 laser radiation was clearly proven to arise from classical rectification. Previous attempts to develop fully lithographic MIM diodes, on the other hand, all foundered on the difficulty of separating optical signals due to rectification from those due to thermal mechanisms. The nonlinearity observed in the large area diodes is, according to theory, sufficient to enable observation of photon-assisted tunneling steps, a phenomenon observed at room temperature only recently in GaAs heterostructures.

Recent Publications

M. E. MacDonald, A. Alexanian, R. A. York, Z. Popovic, and E. N. Grossman, "Spectral transmittance of Lossy Printed Resonant-Grid Terahertz Bandpass Filters," IEEE Trans. Micro. Theory Tech., in press.

J. A. Chervenak, K. D. Irwin, E. N. Grossman, K. D. Irwin, J. M. Martinis, C. D. Reintsema, C. A. Allen, D. Bergman, S. H. Moseley, and R. Shafer, "Performance of Multiplexed SQUID Readout for Cryogenic Sensor Arrays," Nuclear Inst. Methods A, in press.

S. Nolen, J. A. Koch, N. Paulter, C. D. Reintsema, and E. N. Grossman, "Antenna-Coupled Niobium Bolometers for mm-Wave Imaging Arrays," Proc. SPIE, in press.

J. A. Chervenak, K. D. Irwin, E. N. Grossman, J. M. Martinis, C. D. Reintsema, and M. E. Huber, "Superconducting Multiplexer for Arrays of Transition Edge Sensors," Appl. Phys. Lett. **74**, 4043-4045 (June 1999).

C. D. Reintsema, E. N. Grossman, J. A. Koch, "Improved VO_2 Microbolometers for Infrared Imaging: Operation on the Semiconducting-Metallic Phase Transition with Negative Electrothermal Feedback," Proc. SPIE **3698**, 190-200 (April 1999).

High T_C Electronics

Technical Contact:
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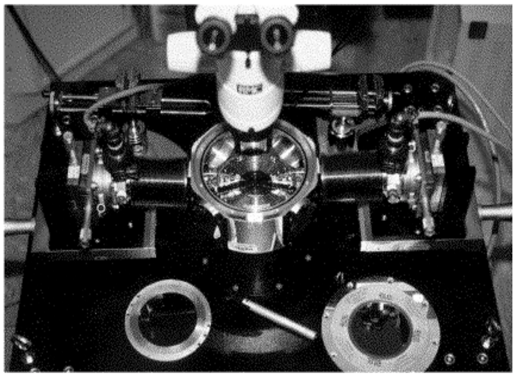
Project Goals

Aid and accelerate the development of high temperature superconductors (HTS) for electronic applications. To this end, we develop innovative measurement techniques and systems and investigate new materials and fabrication processes such as novel thin film oxides and microelectromechanical systems (MEMS).



Cryogenic microwave probe station.

Customer Needs

Customers for the devices being developed include other NIST Divisions responsible for standards and measurement techniques in areas such as the volt; infrared, millimeter-wave, and microwave radiation; and time and frequency standards. The project provides support for the emerging HTS superconducting electronics industry, both through measurements and through the development of HTS devices and circuits. We support other government agencies, including the National Aeronautic and Space Administration (NASA), the Office of Naval Research (ONR), and the Defense Advanced Research Projects Agency (DARPA).

Technical Strategy

We have developed fabrication processes, testing capabilities, and theoretical competence for HTS devices in the areas of microwave, millimeter-wave and terahertz metrology and technology; high sensitivity bolometers; and Josephson junctions. Project staff works with the HTS communication industry to measure and improve the capabilities of HTS devices, and with the Radio-Frequency Technology Division to improve microwave measurement and characterization techniques for HTS films and devices. We collaborate with industry and with the Physics Laboratory's Optical Technology Division to develop and test HTS bolometers for applications such as calibrated radiometers. Other research is conducted on HTS Josephson junctions used in voltage standards, devices, and integrated circuit technology to meet the measurement and application needs of industry. We consider three criteria when selecting research projects: (1) Is it important for standards improvement and development? (2) Is it important but pre-competitive in the commercial sector? (3) Does it include a strong component of new measurement science and technology?

Our goals for research on microwave and millimeter-wave devices in the next year are to build on our unique measurement capabilities to understand the source of undesirable nonlinear behavior in HTS transmission lines and resonators. We will continue to work on a standard for measuring surface resistance at microwave frequencies and methods for the measurement of loss and tunability of ferroelectric thin films and HTS components.

Our research will focus on hot electron bolometers for terahertz mixing using our existing research base in bolometers on Si membranes and in fabricating of sub-micrometer structures in HTS films.

We will use HTS Josephson junctions as models for microwave effects such as harmonic generation. Development of junctions with controllable characteristic voltages, V_C, will continue; high V_C is required for terahertz mixing, detection, and generation, while low V_C is needed for voltage standards.

Further improvements on micromachined ion traps will be realized in the current year. The new Si MEMS facility will be tested and accepted, and process development will begin.

Accomplishments

Microwave Measurements and Devices

Loss and nonlinearity limit the utility of HTS components in communications applications. Superconductivity can significantly improve the sharp band edges of filters, reduce insertion loss in most passive components, and eliminate dispersion in transmission lines. HTS materials have been improved to the point that they rival their low temperature counterparts in surface resistance, R_S; however, power handling and nonlinearity are not yet fully understood or controlled in the manufacturing environment.

The project (1) works with international standards organizations, the International Electrotechnical Commission (IEC) and Versailles Agreement on Advanced Materials and

Standards (VAMAS), to develop a standard for measuring R_S; (2) works on new, calibrated measurement techniques for power dependent effects, especially nonlinearity; (3) develops novel devices for tuning microwave circuits by investigating new materials and structures. A unique cryogenic microwave probe station (see photograph) is an indispensable tool for the work on patterned devices.

- Draft Standard Planned – A draft standard for R_S using dielectric resonators is currently being discussed in a committee of six countries with project participation.

- Model System for HTS Structures – We have developed a model system to investigate different HTS structures for nonlinear microwave response, and can test a variety of thin films, fabrication processes, and structure dimensions to achieve improved performance.

- Calibrated Measurements for Ferroelectric Films – Using the cryogenic probe station, we have studied ferroelectric thin films for tunability and loss. We have developed new and fully calibrated measurement techniques that will enable other groups to better compare materials and devices.

Bolometers

Bolometric applications use the sharp transition to zero resistance at temperatures accessible by inexpensive cryocoolers. The project has been recognized for developing the first sensitive, composite, infrared bolometer and demonstrating the lowest noise temperatures for devices on sapphire and silicon substrates. Infrared detectors and calibrated radiometers are enabled by these developments, as evidenced by collaborative work with the Physics Laboratory and with two companies.

Josephson Junctions and Integrated Circuits

- Record for Characteristic Voltages – The highest V_C in microfabricated junctions was achieved by this project. In collaboration with other research groups, junctions for voltage standards have been measured. Research on grain boundary junctions has been successful in explaining unwanted weak link effects in passive microwave devices.

Micromachining and MEMS

- Micromachined Structures for Ion Traps – We have made micromachined structures for use in ion traps, in collaboration with the Physics Laboratory's Time and Frequency Division. Ions have been trapped successfully, validating this approach for the next generation of frequency standards and other quantum mechanical systems.

- MEMS Facility – We have carried out facility improvements to enable the fabrication this year of Si MEMS. A new addition to the cleanroom has been constructed, incorporating furnaces for Si processing.

Recent Publications

J. C. Booth, J. A. Beall, D. A. Rudman, L. R. Vale, and R. H. Ono, "Geometry Dependence of Nonlinear Effects in High Temperature Superconducting Transmission Lines at Microwave Frequencies," J. Appl. Phys. **86**, 1020-1027 (July 1999).

J. C. Booth, and C. L. Holloway, "Conductor Loss in Superconducting Planar Structures: Calculations and Measurements," IEEE Trans. Micro. Theory Tech. **47**, 769-773 (June 1999).

J. H. Claassen, J. C. Booth, J. A. Beall, D. A. Rudman, L. R. Vale, R. H. Ono, "Nonlinear Inductive Response of High Temperature Superconducting Films Measured by the Mutual Inductance Technique," Appl. Phys. Lett. **74**, 4023-4025 (June 1999).

D. A. Rudman, F. J. B. Stork, J. C. Booth, J. Y. Juang, L. R. Vale, G. J. Beatty, C. I. Williams, J. A. Beall, R. H. Ono, S. B. Qadri, M . S. Osofsky, E. F. Shelton, J. H. Classen, G. Gibson, J. L. MacManus-Driscoll, N. Malde, and L. F. Cohen, "Role of Oxygen Pressure during Deposition on the Microwave Properties YBCO Films," IEEE Trans. Appl. Supercond. **9**, 2460-2464 (June 1999).

D. G. McDonald , R. J. Phelan, Jr., L. R. Vale, R. H. Ono, and D. A. Rudman, "Passivation, Transition Width, and Noise for YBCO Bolometers on Silicon," IEEE Trans. Appl. Supercond. **9**, 4471-4474 (June 1999).

J. C. Booth, J. A. Beall, D. A. Rudman, L. R. Vale, R. H. Ono, C. L. Holloway, S. B. Qadri, M. S. Osofsky, E. F. Shelton, J. H. Classen, G. Gibson, J. L. MacManus-Driscoll, N. Malde, and L. F. Cohen, "Simultaneous Optimization of the Linear and Nonlinear. Microwave Response of YBCO Films and Devices," IEEE Trans. Appl. Supercond. **9**, 4176-4179 (June 1999).

H. Q. Li, R. H. Ono, L. R. Vale, D. A. Rudman, and S. H. Liou, "Interactions Between Bicrystal Josephson Junctions in a Multilayer Structure," IEEE Trans. Appl. Supercond. **9**, 3417-3420 (June 1999).

L. R. Vale, R. H. Ono, J. Talvacchio, M. G. Forrester, B. D. Hunt, M. S. DiIorio, K-Y Yang, and S. Yoshizumi, "Long Term Stability of YBCO Based Josephson Junctions," IEEE Trans. Appl. Supercond. **9**, 3382-3385 (June 1999).

Appendix A:
Major Laboratory Facilities

Clean Room

Our facilities for fabricating integrated circuits are essential to nearly all of the work in the Division. We maintain a research-class facility for superconductor and magnetic structures. Beginning with computer aided design, we use electron beam and optical lithography to make structures smaller than 100 nanometers and complex circuits containing as many as 32 000 Josephson junctions. Our tools are housed in 200 square meters of “class 100” cleanroom space which was improved greatly in 1999. We also added tools for fabricating microelectromechanical systems (MEMS), which have been essential in the past for many of our ultra-sensitive instruments, and for micromachined ion traps for future clocks. We will soon apply these techniques to novel magnetic instruments.

Our near state-of-the-art facilities are open-shop. All of our staff, and occasional visitors, can personally use them after appropriate training. Our processes are flexible to avoid constraining research activities to fixed design rules and to allow maximum creativity. Our past accomplishments are testimony to the success of our approach. A partial list of the tools we use follows.

Facilities for Fabrication

Optical lithography, e-beam lithography, superconductor integrated circuit fabrication, magnetic thin film deposition and circuit fabrication, microelectromechnaical systems (MEMS) fabrication, ultra-high vacuum magnetic thin film deposition and *in situ* analysis, and laser ablation of high temperature superconductor thin films.

Experimental Environments

Dilution refrigerator for temperatures down to 30 millikelvins, adiabatic demagnetization refrigerators for cooling to 50 millikelvins, large bore superconducting magnets up to 12 teslas.

Instruments

Instruments for measuring properties of magnetic thin films, magneto-optic Kerr effect (MOKE), time-resolved second-harmonic magneto-optic Kerr effect (SHMOKE), vibrating sample magnetometer, alternating gradient force magnetometer, induction-field looper, AC susceptometer, SQUID magnetometer, high speed electrical test facilities, industry standard spin stand, atomic force microscope and magnetic force microscope, high current measurement of superconductor critical current, high resolution X-ray materials analysis, X-ray structural analysis, high resolution mass spectrometer with electrospray source, Josephson voltage standards, characterization of microwave loss for thin films, variable temperature microwave probe station, characterization of infrared antennas.

Appendix B: Postdoctoral Opportunities

NIST offers postdoctoral associateships in collaboration with the National Research Council (NRC). Research topics and associated advisors for the Electromagnetic Technology Division are listed below. Please see our Web information at emtech.boulder.nist.gov for full details on each opportunity. Contact a prospective advisor to discuss details of proposed work and the application process. If you do not find a topic that exactly matches your interest, please contact an advisor in a similar discipline. U.S. citizenship is required for postdoctoral appointments.

Research Topic	Advisor
Metrological Applications of Cold Electrons	
DNA Sequencing Using a Cryogenic Mass Spectrometer	Gene Hilton
Fabricating Superconducting Devices and Circuits	Sam Benz
High-T_C Superconducting Films and Interfaces	Ron Ono
High-Resolution Microcalorimeters for X-Ray Microanalysis	John Martinis
High-T_C Superconductors: Devices, Device Physics, and Circuits	Ron Ono
High-T_C Superconductors: Microwave Properties and Devices	Ron Ono
Physics and Applications of Single Electron Tunneling Devices	Mark Keller
Superconducting Devices for Infrared to Millimeter-Wave Applications	Erich Grossman
Superconducting Detectors for Photons from Infrared through X-Rays	John Martinis
Superconducting Terahertz-Frequency Oscillators	Sam Benz
Metrology for the Superconductivity Industry	
High-T_C Superconducting Measurements and Materials	Jack Ekin
High-T_C Superconducting Thin Films for Devices	Jack Ekin
Low-T_C Superconductor Measurements	Jack Ekin
Superconductor Measurements	Loren Goodrich
Metrology for Magnetic Data Storage	
Atomic Scale Information Storage	John Moreland
High-Speed Magnetic Phenomena	Tom Silva
Magnetic Measurements for the Data Storage Industry	Ron Goldfarb
Magnetic Resonance Force Microscopy	John Moreland
Magnetism in Thin Films and Surfaces	David Pappas
Micro-electromechanical Systems for Metrology	John Moreland
Nanoscale Imaging for Magnetic Technology	John Moreland
Nanoscale Magnetic Structures	Steve Russek
Nonlinear Magneto-Optics	Tom Silva
Properties of Nanometric Magnetic Particles and Ultrathin Films	Ron Goldfarb
Spin-Dependent Electron Transport in Metals and Conducting Oxides	Steve Russek
Thermal Instability of Magnetic Thin Films	Tom Silva

Appendix C:
Electromagnetic Technology Division Staff

3776 Harris, Richard E., Chief
3678 Bradford, Ann, Secretary
3812 Schump, Jeanne, Administrative Officer
3811 Simmon, Mary Jo, Administrative Assistant
3988 McCarthy, Sandy; 5477 Corwin, Ruth; Secretaries

Magnetic Recording Metrology

3374 Pappas, David (PL)
3381 Arnold, Stephen (Ctr)

Magnetic Instruments and Materials Characterization

3650 Goldfarb, Ron (PL)
3701 Bailey, Bill (PD)
5191 Jander, Albrecht (PD)
3997 Kabos, Pavel (GR)
7365 Kaka, Shehzu (PREP)
5333 Kos, Tony
5206 Rizzo, Nick (FTT)
5097 Russek, Steve
7826 Silva, Tom
5869 Yee, Gordon (GR)

Nanoprobe Imaging for Magnetic Technology

3641 Moreland, John (PL)

Superconductor Standards and Technology

3143 Goodrich, Loren (PL)
3777 Stauffer, Ted

Superconductor Interfaces and Electrical Transport

5448 Ekin, Jack (PL)
5631 Bray, Steve
3815 Cheggour, Najib (GR)
5441 Clickner, Cam
5345 Collins, Tim (Ctr)
7894 Xu, Yizi (Ctr)
5345 Sesselman, Roland (GR)

Josephson Array Development

5258 Benz, Sam (PL)
3906 Burroughs, Charlie
5211 Dresselhaus, Paul
3740 Hamilton, Clark (GR)

Nanoscale Cryoelectronics

5081 Rudman, David (PL)
5557 Anders, Solveig (GR)
5344 Bergren, Norm
7644 Chervenak, Jay (Ctr)
3461 Deiker, Steven (PD)
3418 Eichenberger, Ali (GR)
5679 Hilton, Gene
3402 Huber, Martin (Ctr)
5911 Irwin, Kent
3841 Jehl, Xavier (GR)
3391 Kautz, Richard (GR)
5430 Keller, Mark
3597 Martinis, John
3148 Nam, Sae Woo (PD)
3021 Rabin, Michael (PD)
5606 Neil, Patricia (PREP)
7457 Wollman, David

High Performance Sensors, Infrared Detectors, and Mixers

5102 Grossman, Erich (PL)
3340 Harvey, Todd
3114 Nolen, Shalva (PD)
5052 Reintsema, Carl

High T_C Electronics

3762 Ono, Ron (PL)
5989 Beall, Jim
7900 Booth, Jim
5049 Crews, Maggie
7064 Koch, Jay
5113 McDonald, Don (GR)
7213 Shimakage, Hisashi (GR)
5121 Vale, Leila

Legend

Ctr = Contractor
FTT = Full Time Temporary
GR = Guest Research Scientist
PD = Postdoctoral Research Associate
PL = Project Leader
PREP = Professional Research Experience Program Student

Telephone numbers are (303) 497-(extension number shown)

Appendix D: Prefixes for the International System of Units (SI)

Multiplication Factor	Prefix	Symbol	Multiplication Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	µ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y